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OVERVIEW OF THE AEROTHERMAL ENVIRONMENT OF AIR-LAUNCHED MISSILE--ETC(U)
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Overview of the Aerothermal Environment of Air-Launched Missiles

by
B. M. Ryan
Ordnance Systems Department

DECEMBER 1981

NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

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Naval Weapons Center

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FOREWORD

This technical publication presents an overview of how the aerothermal environment is determined and utilized in aerothermodynamic analysis of weapon systems at the Naval Weapons Center. This environment includes atmospheric and climatic temperature data, storage and preflight conditions, captive carry and mission profile influence and, finally and often most important, the free-flight environment. In this report, current work is reviewed; planned work is discussed, and recommendations are made for needed efforts.

Although much of this overview represents long-standing practices developed over a period of time on many weapon programs, the compilation and refinements were supported by the Naval Air Systems Command and executed by the Naval Weapons Center under the Strike Warfare Weaponry Technology Block Program under Work Request 21104, AIRTASK A03W-03P2/008B/OF32-300-000 (appropriation AB1721319). This AIRTASK provides for continued exploratory development in the air superiority and air-to-surface mission areas. Mr. W. C. Volz, AIR-320C, was the cognizant NAVAIR Technology Administrator. This report was reviewed for technical accuracy by C. F. Markarian.

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(U) *Overview of the Aerothermal Environment of Air-Launched Missiles,* by B. M. Ryan. China Lake, Calif., Naval Weapons Center, December 1981. 58 pp. (NWC TP 6292, publication UNCLASSIFIED.)

(U) The aerothermal environment of a weapon system begins with the storage and preflight conditions which determine the initial flight temperatures and influence the captive-carry temperature response of the missile. The performance capability of the carrying aircraft and the operational techniques and mission profiles required by current tactics define the captive flight thermal environment. All these factors determine the temperature distribution of the missile at launch, which becomes the initial condition for calculating the temperature response during the free-flight trajectory. The missile configuration affects the temperature response during all phases of flight. Fundamental to the determination of these temperatures is the effect of meteorological and climatic conditions due to the atmospheric temperature distribution which changes substantially as a result of seasonal and geographic effects as well as altitude. The high Mach numbers and extended flight times of the modern high-performance carrying aircraft and of current and proposed highly sophisticated advanced missile systems make detailed consideration and understanding of these effects essential. This report presents an overview of these environmental factors as they are currently understood and employed at the Naval Weapons Center. Also discussed are problem areas and knowledge gaps, particularly in the free-flight environment.

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INTRODUCTION

The thermal environments of concern in the design of a weapon system must include the entire life cycle of the missile (in particular, preflight, captive flight, and free flight). The storage and preflight climatic conditions, if not considered and accounted for, could cause deterioration of systems prior to use if long-term temperatures were excessive. In captive flight, low temperatures are experienced during long duration cruise or maximum endurance flight at high altitude. Extreme flight conditions of this nature can cold soak a weapon to levels that will cause performance problems with such components as electronics, thermal batteries, propellant grains, and fuel systems. Maximum skin temperatures in captive flight occur during a supersonic dash, and maximum internal temperatures can be caused by long duration flights at low altitudes and high subsonic speeds. Thermal problems associated with hot captive flight profiles generally involve exceeding the temperature limitations of internal electronic components, explosives, and solid and liquid fuels. The powered missile in free flight can propel itself to high Mach numbers for long enough time periods to cause extreme aerodynamic heating, which can result in structural degradation of the airframe as well as thermal problems in the propellant, explosive, fuzing system, guidance section, and other components. Trends toward higher Mach numbers and longer range have made internal heating a major free-flight problem in current and planned weapons systems. Additionally, severe localized heating problems can be caused by aerodynamic interference problems generated by both conventional designs and unusual configurations which may be associated with advanced designs. Accurate knowledge and understanding of these problem areas can aid in intelligent design for solutions to the problems. Solutions can include thermal insulation, active heating and cooling, and selection of exotic materials that will allow the design to survive and operate in the real thermal environment.

Since the thermal design of a system is driven by the definition of the thermal environment, extreme care must be taken in the identification of the flight profiles, trajectories, and model atmospheres which make up this environment. Severe penalties in terms of cost, performance, and reliability of a system can result if the design thermal environment is overspecified or underspecified. An overly complex design increases costs and lowers reliability. Unnecessary insulation and cooling/heating can lead to reduced performance, higher cost, and diminished reliability. On the other hand, underdesign can lead to failure or inability to adequately accomplish the mission. In every weapon program at the Naval Weapons Center (NWC), the thermal environment had to be determined and selected before the actual thermal analysis of the weapon system was started and even before specification and requirements were established. Much of the effort has been carried out piecemeal; hence, previous and even current work may be duplicated. Thus, a systematic compilation and investigation have been initiated to gather in one place all the preliminary data necessary to

conduct a thorough thermal analysis. These data include reasonable extreme atmospheres and performance characteristics of current aircraft that could carry the weapon. For a specific weapon it will always be necessary to determine in advance how the weapon system being analyzed will be used (or could grow), so that a proper, practical, and realistic thermal environment can be selected. This report presents an overview of the general philosophy and techniques currently in use at NWC for this purpose. Details of the specific environmental areas will be discussed in separate, classified documents.

MODEL ATMOSPHERES

Fundamental to all the thermal environments to which a missile may be exposed is the atmospheric temperature. In addition to dependence on height above the surface, atmospheric temperature is a function of meteorological conditions which may establish a "hot" or "cold" atmosphere and climatic conditions which are a function of season and geographical location. The ambient temperature of the atmosphere is a key factor in computing the recovery temperature which drives the aerodynamic heating of a body in flight.

Over the years, a number of "standard" atmospheres have been developed to satisfy a need for standardization of aircraft instruments and aircraft performance.[1-7] The World Meteorological Organization defines the standard atmosphere in part as follows:[7]

> "a hypothetical vertical distribution of atmospheric temperature, pressure and density which, by international agreement, is roughly representative of year-round, mid-latitude condition . . . The air is assumed to obey the perfect gas law and hydrostatic equation which, taken together, relate temperature, pressure and density with geopotential . . . This atmosphere shall also be considered to rotate with the earth, and be an average over the diurnal cycle, semi-annual variation . . ."

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[1] *Standard Atmosphere - Tables and Data for Altitudes to 65,000 Feet* 1955. (NACA Report 1235, supersedes NACA TN 3182; publication UNCLASSIFIED.)

[2] Air Force Cambridge Research Center. *The ARDC Model Atmosphere, 1959*, by R. A. Minzner, K. S. W. Champion, and H. L. Pond. AFCRC, August 1959. (Air Force Surveys in Geophysics No. 115, AFCRD-TR-59-267, publication UNCLASSIFIED.)

[3] International Civil Aviation Organization. *Manual of the ICAO Standard Atmosphere* Washington, D. C., U. S. Government Printing Office, 1964.

[4] International Standards Organization. *Draft International Standard* 1973. (ISO/DIS 253, publication UNCLASSIFIED.)

[5] United States Committee on Extension to the Standard Atmosphere *U S Standard Atmosphere, 1962*. Washington D C., U. S. Government Printing Office, 1962.

[6] ------. *U.S. Standard Atmosphere Supplements, 1966* Washington, D.C., U.S. Government Printing Office, 1967.

[7] ------. *U S Standard Atmosphere, 1976*. Washington, D.C., U.S. Government Printing Office, 1976.

The standard atmosphere currently in use is the U. S. Standard Atmosphere, 1976.[7] This atmosphere differs from other commonly used atmospheres only above 50 kilometers (about 164,000 feet)[4,5] or above 32 kilometers (about 105,000 feet).[3] Below 86 kilometers (about 282,000 feet), the following equilibrium assumptions apply:

1. Air is dry.

2. Air is homogeneous (constant mean molecular weight).

3. Air is a perfect gas: $P = \rho R^*T/M$.

4. Air obeys the hydrostatic equation: $dP = -g\rho dZ$.

(Definitions of the symbols and values of the pertinent constants are listed under *Nomenclature* at the end of this report.)

It had long been recognized that somewhat systematic variations in atmospheres exist due to geography (latitude) and season. These variations have been reasonably well defined in the lower altitude levels of interest to missile designers and were presented in a supplement to the Standard Atmosphere, 1966.[6] These atmosphere models are based on northern hemispherical data but are probably good to mid-latitudes of the southern hemisphere. The seasonal variations at the equator (latitude 0°) are minimal. Thus, the atmosphere model near the equator (latitude 15°) is presented only as an annual average. Model atmospheres for higher latitudes (30° N, 45° N, 60° N, 75° N) are presented for winter (January) and summer (July). In addition, cold and warm atmospheres for January are given for 60° N and 75° N. These atmospheres differ from the winter atmospheres only at altitudes above about 8.5 kilometers (about 27,900 feet). Not enough data were available to develop an arctic (latitude 90° N) atmosphere, but the 75° N atmosphere should be a close approximation. Also given is a mid-latitude spring/fall atmosphere which is the same as the standard atmosphere to an altitude of 69 kilometers (about 226,400 feet). The gravitational accelerations, temperature, and pressure at sea level for each of the supplemental atmospheres are given in Table 1. (An update and extension of this information has been published.)[8]

These standard and supplemental atmospheres, however, are average conditions and do not represent the extremes that can occur. The design of military equipment to withstand and operate in extreme climatic conditions requires calculation of system temperature response in atmospheric conditions that are extreme rather than average. Consideration must be given to simultaneous use of both realistic conditions and conditions which result in an extreme temperature response by the weapon system. The background to the recognition of and response to this need has been published.[9] The envelopes of extreme temperatures developed have been tabulated in MIL-STD-210B.[10]

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[8] Allen E. Cole and Arthur J. Kantor. *Air Force Reference Atmospheres.* 28 February 1978. (AFGL-TR-78-0051, publication UNCLASSIFIED.)

[9] N. Sissenwine and R. V. Cormier. *Synopsis of Background Material for MIL-STD-210B, Climatic Extremes for Military Equipment.* January 1974. (AFCRL-TR-74-0052, publication UNCLASSIFIED.)

[10] Department of Defense. *Military Standard Climatic Extremes for Military Equipment.* 15 December 1973. (MIL-STD-210B, publication UNCLASSIFIED.)

TABLE 1. Sea Level Gravitational Acceleration, Temperature, and Pressure of Supplemental Model Atmospheres.

Latitude	Month	g_0, m/s^2	T_0, K, °C	P, N/m^2	g_0, ft/sec^2	T_0, R, °F	P_0, lb/ft^2
15° N	Annual	9.78381	302.59, 29.44	101 325	32.09 911	544.64, 84.99	2116.22
30° N	January	9.79324	288.52, 15.37	102 136	32.09 724	519.33, 59.66	2113.15
30° N	July		304.58, 31.43	101 325		548.25, 88.58	2116.22
45° N	January	9.80665	272.59, -0.56	101 832	32.17 405	490.67, 31.00	2126.80
45° N	July		296.22, 23.07	101 325		533.19, 73.52	2116.22
(1) Mid	Spring/fall		288.15, 15.00	101 325		518.67, 59.00	2116.22
Standard			288.15, 15.00	101 325		518.67, 59.00	2116.22
60° N	January	9.81911	257.28, -15.87	101 325	32.21 493	463.11, 3.44	2116.22
(2) 60° N	January (cold)		257.28, -15.87	101 325		463.11, 3.44	2116.22
(3) 60° N	January (warm)		257.28, -15.87	101 325		463.11, 3.44	2116.22
60° N	July		288.45, 15.30	101 021		519.21, 59.54	2109.87
75° N	January	9.82860	249.22, -23.93	101 325	32.24 606	448.59, -11.08	2116.22
(4) 75° N	January (cold)		249.22, -23.93	101 325		448.59, -11.08	2116.22
(4) 75° N	January (warm)		249.22, -23.93	101 325		448.59, -11.08	2116.22
75° N	July		278.92, 5.77	101 224		502.06, 42.39	2114.10

(1) Standard 0 to 69 km
(2) 60° N January 0 to 12 km
(3) 60° N January 0 to 8.5 km
(4) 75° N January 0 to 8.5 km

An important limitation of the MIL-STD-210B upper air temperatures, and one that is often overlooked, is that they are envelopes of world-wide extreme values. They are not hydrodynamically consistent temperature profiles which could exist at a given place and time, as is the case with the standard and supplemental atmospheres. An example of the widely varying locations involved is shown in Figure 1 for hot and cold temperature extremes. (Note that hot temperatures are sometimes associated with "cold" locations and cold temperatures with "hot" locations.) As a result, the MIL-STD-210B envelopes are not intended for use in aerothermal analyses of aircraft and missiles traversing large altitude changes. The values which make up the MIL-STD-210B envelopes represent the temperature at each altitude which has been equalled or exceeded in the stated percentage of the hourly temperature readings (1% for the recommended operational extremes) during the most extreme month in the most extreme part of the world. A comparison of the Standard Atmosphere with the 1% and 10% MIL-STD-210B atmospheric temperature envelopes is shown in Figure 2.

As stated previously, the report of footnote 10 recommends that the 1% risk be used for temperatures related to the operational environment. The practice at NWC has been to use the 10% risk for operations (except where lives would be endangered), as the 1% risk is considered too severe and often results in unacceptable design penalties. In any event, when one selects the risk to be assumed, the planned use of the weapon system should be considered. Extreme care should be taken to avoid the several-layered combination of extreme probability conditions and yet still design for the realistically extreme conditions that could be encountered.

In addition to the world-wide air environments described above, envelopes developed for extreme naval air environments have taken into account the moderating influence of the ocean. A comparison of these atmospheric profiles with world-wide and standard profiles is shown in Figure 3. A summary of all these atmospheric models is given in Table 2.

Temperature profiles which are consistent with the MIL-STD-210B extremes but are suitable for use in thermal analyses of altitude varying trajectories have been developed by the Naval Postgraduate School, Monterey.[11-13] This task was approached by using the data from which the extremes of MIL-STD-210B were obtained. An example of the data used to obtain the envelopes of MIL-STD-210B is shown in Figure 4, which indicates that the temperature at one altitude of each real atmosphere corresponds to one point on the MIL-STD-210B envelope of extremes. Actual temperature profiles which contain the extreme at a given altitude are averaged to give a profile representative of that extreme. In this manner, a family of temperature profiles is generated, each containing the MIL-STD-210B extreme at a specific altitude. The analyst may then select the real atmosphere with an extreme at an altitude of most application to his particular study. Examples of realistic cold and hot atmospheres

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[11] Naval Postgraduate School. *Development of Regional Extreme Model Atmospheres for Aerothermodynamic Calculations (I)*, by F. L. Martin. Monterey, CA, NPS, 20 October 1972. (NPS-51MR72101A, publication UNCLASSIFIED.)

[12] ------. *Develpment of Regional Extreme Model Atmospheres for Aerothermodynamic Calculations (II)*, by F. L. Martin. Monterey, CA, NPS, 1 July 1973. (NPS-51MR73071A, publication UNCLASSIFIED.)

[13] ------. *Oceanic Extreme Model Atmospheres for Aerothermodynamic Calculations*, by F. L. Martin. Monterey, CA, NPS. (NPS-51MR74091A, publication UNCLASSIFIED.)

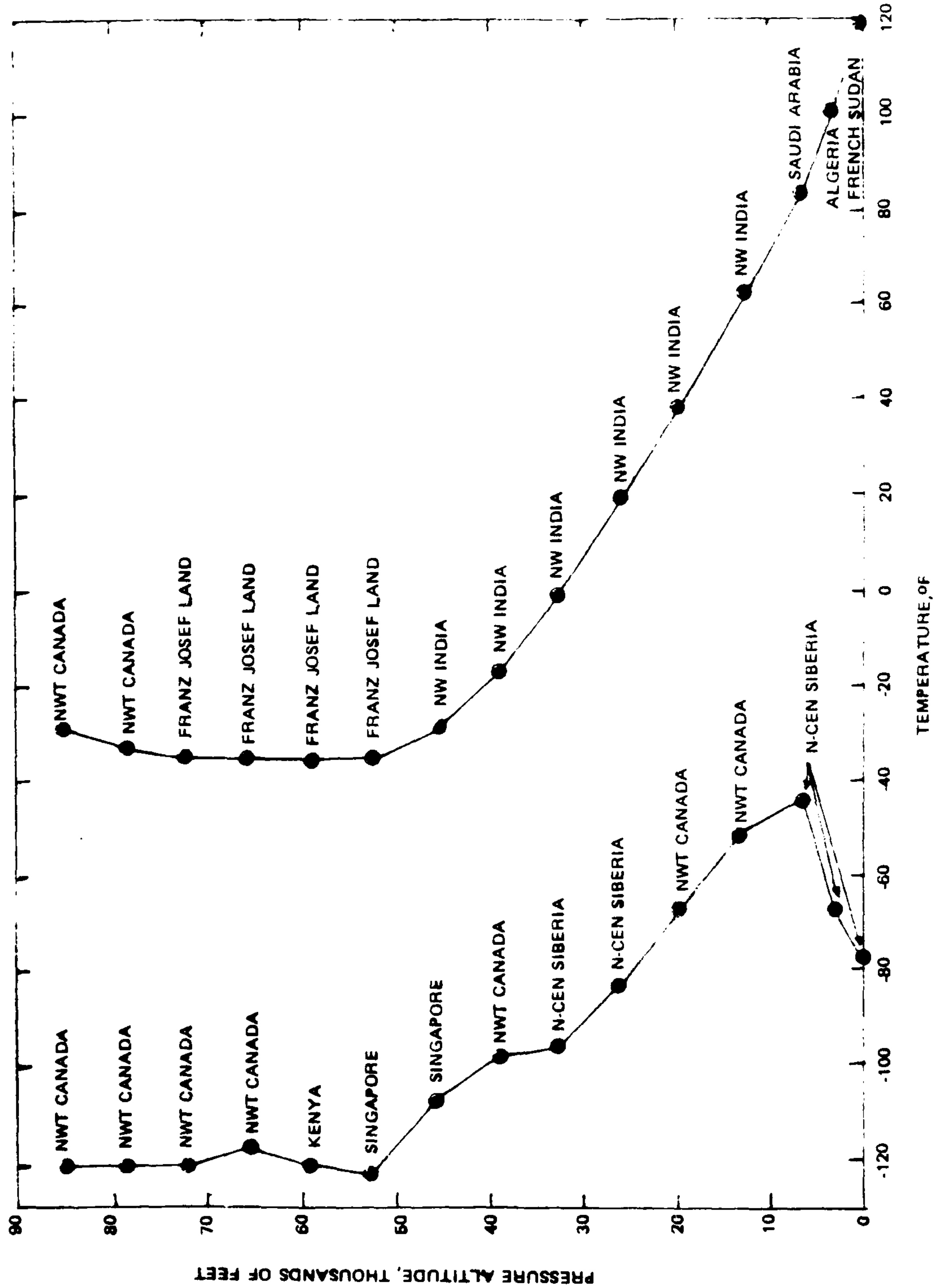

FIGURE 1. Locations Corresponding to MIL-STD-210B 1% Temperature Extremes.

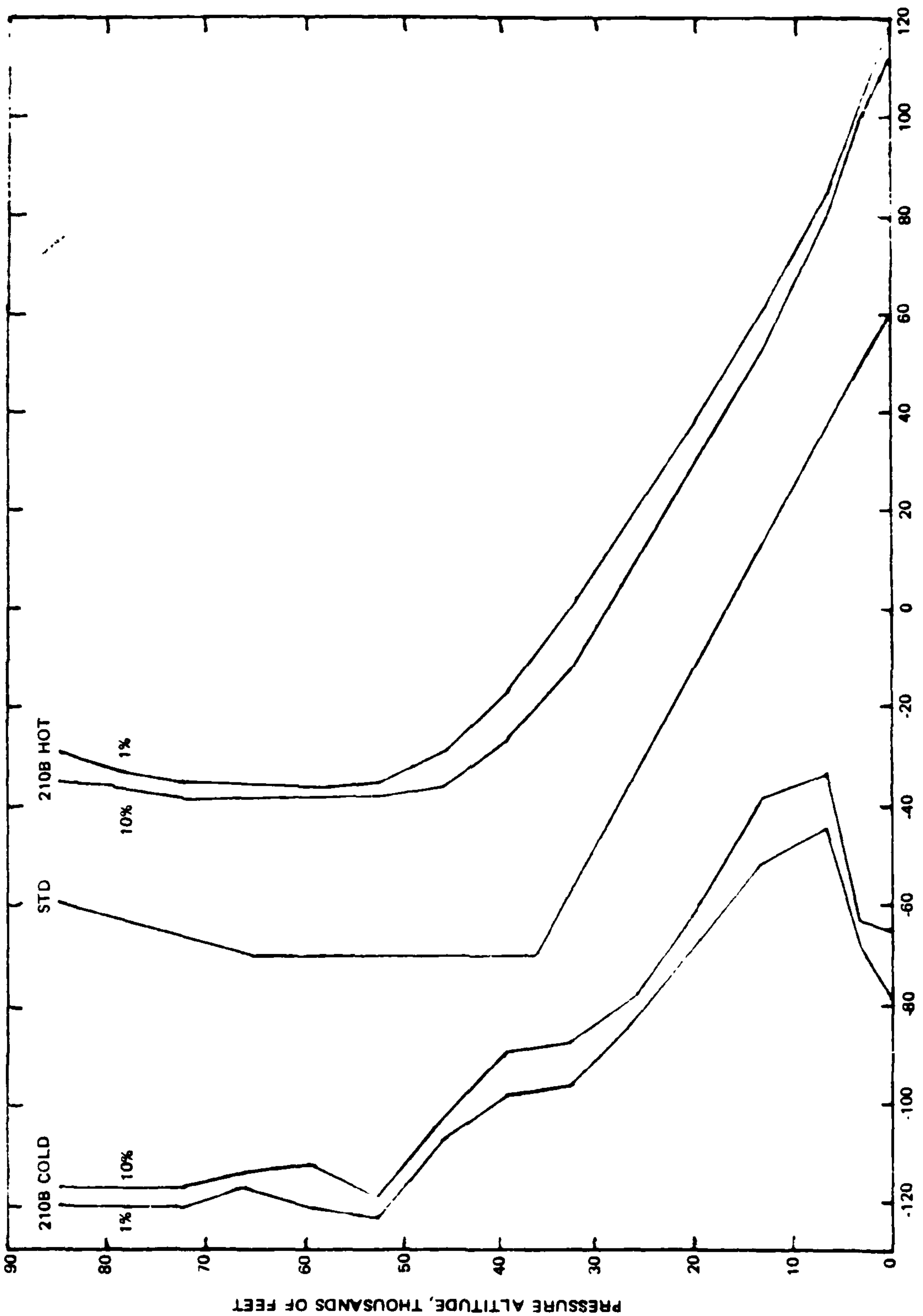

FIGURE 2. U.S. Standard and MIL-STD-210B Atmospheric Temperature Profiles.

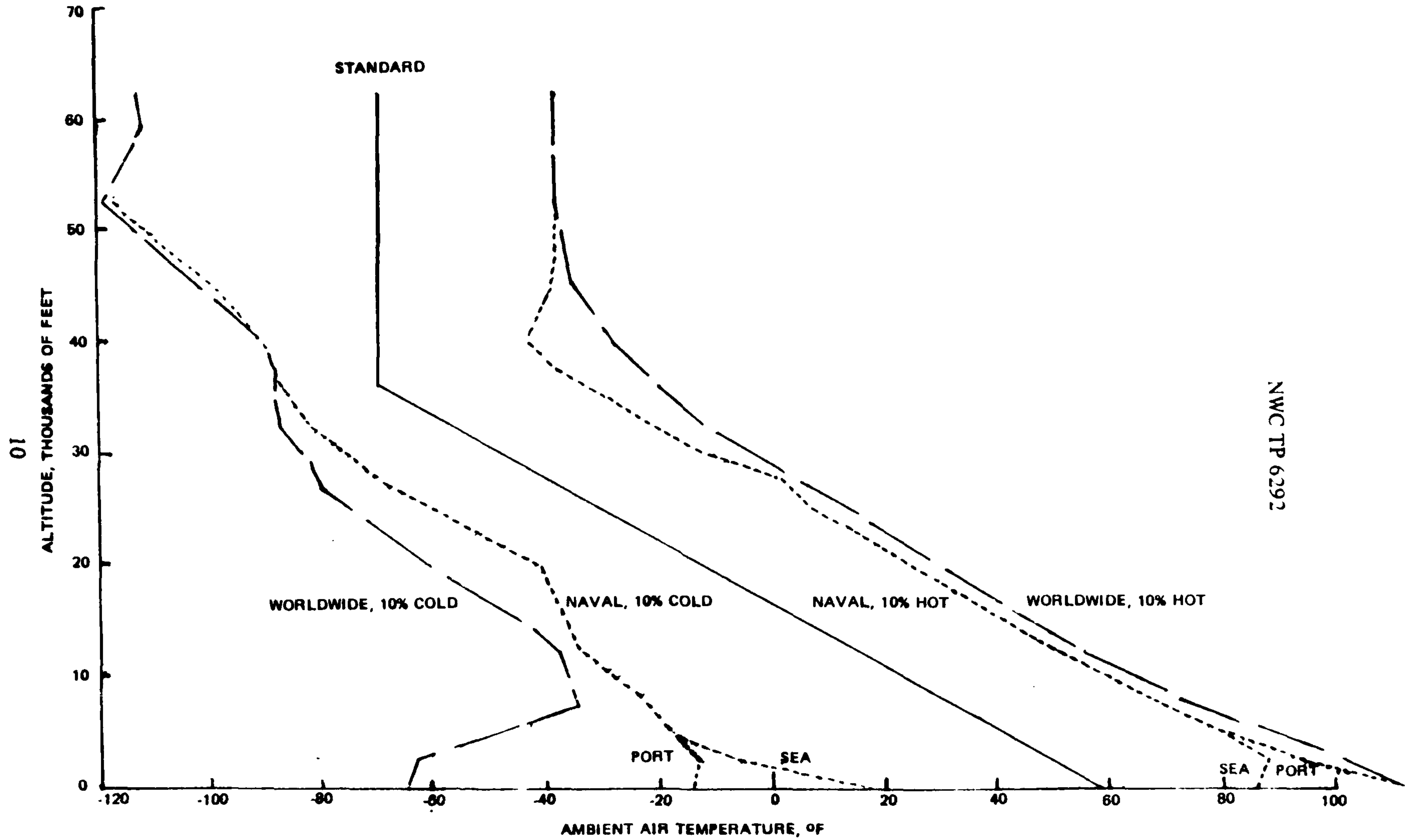

FIGURE 3. Standard Atmosphere Model and Envelopes of Naval and Worldwide Atmosphere Extremes.

TABLE 2. Summary of Standard, Supplemental and E

Altitude, km (feet)	Standard, °C (°F)	High 1%,[a] °C (°F)	High 5%,[a] °C (°F)	High 10%,[a] °C (°F)	High 20%,[a] °C (°F)	Low 1%,[a] °C (°F)	Low 5%,[a] °C (°F)	Low 10%,[a] °C (°F)	Low 20%,[a] °C (°F)	Highest,[a] °C (°F)	Lowest,[a] °C (°F)	Highest Naval,[a] °C (°F)	Lowest Naval,[a] °C (°F)	H 1 °C
														sea 3
0 (0)	15 (59)	49(120)	46(115)	45(113)		-61(-78)	-57(-70)	-54(-65)	-51(-60)	58(136)	-68(-90)	51(123)	-38(-37)	4
1 (3281)	8.5 (47)	39(102)	38(100)	37(99)	34(93)	-55(-67)	-54(-65)	-53(-63)	-52(-62)	40(104)	-56(-69)	34(93)	-33(-27)	3
2 (6562)	2.0 (36)	29(84)	27(81)	26(79)	25(77)	-42(-44)	-38(-36)	-36(-33)	-33(-27)	31(88)	-47(-53)	24(77)	-34(-29)	2
4 (13,123)	-11 (12)	16(61)	13(55)	11(52)	10(50)	-46(-51)	-43(-45)	-39(-38)	-37(-35)	19(66)	-51(-60)	14(57)	-41(-42)	1
6 (19,685)	-24 (-11)	4(39)	1(34)	-1(30)	-2(28)	-55(-67)	-52(-62)	-51(-60)	-48(-54)	6(43)	-60(-76)	0(32)	-48(-54)	-2
8 (26,247)	-37 (-35)	-7(19)	-11(12)	-13(9)	-14(7)	-64(-83)	-61(-78)	-61(-78)	-59(-74)	-4(25)	-64(-83)	-10(14)	-60(-76)	-1
10 (32,808)	-50 (-58)	-18(0)	-23(19)	-25(-13)	-26(-15)	-71(-96)	-69(-92)	-66(-87)	-64(-83)	-18(0)	-72(-98)	-24(-11)	-70(-94)	-[illegible]
11 (36,089)	-56.5 (-69.7)													
12 (39,370)	-56.5 (-69.7)	-27(-17)	-32(-26)	-33(-27)	-37(-35)	-72(-98)	-70(-94)	-67(-89)	-65(-85)	-27(17)	-77(-107)	-36(-33)	-74(-101)	-[illegible]
14 (45,932)	-56.5 (-69.7)	-34(-29)	-37(-35)	-38(-36)	-40(-40)	-77(-107)	-76(-105)	-75(-103)	-73(-99)	-34(29)	-78(-108)	-35(-31)	-78(-109)	-[illegible]
16 (52,493)	-56.5 (-69.7)	-37(-35)	-39(-38)	-39(-38)	-40(-40)	-86(-123)	-85(-121)	-84(-119)	-83(-117)	-35(31)	-87(-125)	-35(-31)	-87(-125)	-[illegible]
18 (59,055)	-56.5 (-69.7)	-38(-36)	-39(-38)	-39(-38)	-40(-40)	-85(-121)	-82(-116)	-80(-112)	-79(-110)	-34(-29)	-85(-121)			
20 (65,617)	-56.5 (-69.7)	-37(-35)	-39(-38)	-39(-38)	-40(-40)	-83(-117)	-82(-116)	-81(-114)	-77(-103)	-33(-27)	-83(-117)			
22 (72,178)	-54.5 (-66)	-37(-35)	-38(-36)	-39(-38)	-40(-40)	-85(-121)	-84(-119)	-83(-117)	-79(-110)	-36(-33)	-85(-121)			
24 (78,740)	-52.5 (-62)	-36(-33)	-38(-36)	-38(-36)	-39(-38)	-85(-121)	-84(-119)	-83(-117)	-82(-116)	-31(-24)	-85(-121)			
26 (85,302)	-50.5 (-59)	-34(-29)	-36(-33)	-37(-35)	-37(-35)	-85(-121)	-84(-119)	-83(-117)	-82(-116)	-32(-26)	-85(-121)			
28 (91,864)	-48.5 (-55)	-30(-22)	-34(-29)	-34(-29)	-35(-31)	-85(-121)	-83(-117)	-82(-116)	-81(-114)	-30(-22)	-85(-121)			
30 (98,425)	-46.5 (-52)	-30(-22)	-30(-22)	-31(-24)	-32(-26)	-84(-119)	-83(-117)	-81(-114)	-79(-110)	-28(18)	-85(-121)			

[a]Envelopes of extreme temperatures taken from MIL-STD-210B (Reference 10). Not internally consistent atmospheres and should not be used in analyses with vary

[b]Internally consistent atmospheres. Taken from U.S. Standard Atmosphere Supplements (Reference 6).

[c]Same as standard.

al and Extreme Atmosphere Profiles. (Note: See references for intermediate points in case of supplemental at atmospheres.)

est a F)	High 1%,[a] °C (°F)	High 5%,[a] °C (°F)	High 10%,[a] °C (°F)	High 20%,[a] °C (°F)	Low 1%,[a] °C (°F)	Low 5%,[a] °C (°F)	Low 10%,[a] °C (°F)	Low 20%,[a] °C (°F)	15° N annual,[b] °C (°F)	30° N January,[b] °C (°F)	30° N July,[b] °C (°F)	45° N January,[b] °C (°F)	45° N July,[b] °C (°F)	Mid-latitude spring/fall,[c] °C (°F)	60° N January,[b] °C (°F)	6 Ja (co °C
	sea 33(92)	31(88)	30(86)	29(85)	-14(7)	-10(14)	-8(18)	-6(21)								
7)	48(119)	46(114)	45(113)	43(109)	-24(-30)	-28(-19)	-25(-14)	-22(-7)	29(85)	15(60)	31(89)	0(31)	23(74)	15(59)	-16(3)	-16
7)	33(91)	32(90)	31(88)	31(88)	-31(-24)	-26(-15)	-25(-13)	-23(-9)	23(73)	12(54)	22(72)	-4(25)	18(64)	8.5(47)	-14(7)	-14
9)	24(75)	23(73)	22(72)	22(72)	-33(-27)	-30(-22)	-29(-20)	-27(-17)	16(61)	9(48)	16(62)	-8(18)	13(55)	2(36)	-17(1)	-17
2)	12(54)	10(50)	9(48)	9(48)	-40(-40)	-38(-36)	-37(-35)	-36(-33)	4(40)	-5(23)	5(40)	-17(1)	0(33)	-11(12)	-25(-14)	-25
4)	-2(28)	-3(27)	-4(25)	-4(25)	-47(-53)	-41(-42)	-40(-40)	-38(-36)	-9(15)	-18(0)	-7(20)	-29(-21)	-12(11)	-24(-11)	-39(-38)	-39
6)	-14(7)	-15(5)	-16(3)	-16(3)	-58(-72)	-57(-71)	-54(-65)	-53(-63)	-23(-9)	-31(-24)	-21(-6)	-41(-43)	-25(-13)	-37(-35)	-53(-62)	-53
4)	-27(-17)	-28(-18)	-30(22)	-30(22)	-69(-92)	-65(-85)	-64(-83)	-62(-80)	-36(-34)	-44(-47)	-35(-31)	-53.5(-64)	-38(-36)	-50(-58)	-56(-69)	-56
														-56.5(-69.7)		
01)	-39(-38)	-40(-40)	-42(-44)	-43(45)	-73(-99)	-69(-92)	-68(-90)	-66(-87)	-50(-58)	-57(-71)	-49(-56)	-54.5(-66)	-51(-60)	-56.5(-69.7)	-56(-69)	-56
09)	-37(-35)	-38(-36)	-39(-38)	-40(-40)	-77(-107)	-75(-103)	-74(-101)	-73(-99)	-63(-82)	-62(-80)	-63(-81)	-55.5(-68)	-57.5(-72)	-56.5(-69.7)	-56(-69)	-58
25)	-37(-35)	-39(-38)	-39(-38)	-40(-40)	-86(-123)	-84(-119)	-83(-117)	-82(-116)	-77(-106)	-67(-89)	-70(-94)	-56.5(-70)	-57.5(-72)	-56.5(-69.7)	-57(-70)	-60
									-74(-101)	-70(-94)	-66(-86)	-57.5(-72)	-56(-69)	-56.5(-69.7)	-58(-72)	-62
									-66(-87)	-65(-85)	-61(-78)	-58(-72)	-54(-65)	-56.5(-69.7)	-59(-74)	-64
									-58(-72)	-60(-76)	-57(-71)	-58(-72)	-51.5(-61)	-54.5(-66)	-60(-76)	-66
									-54(-64)	-56(-69)	-53(-63)	-58(-72)	-49(-56)	-52.5(-62)	-61(-79)	-68
									-49(-57)	-52(-62)	-49(-56)	-58(-72)	-47(-52)	-50.5(-59)	-61(-78)	-70
									-45(-49)	-48(-54)	-45(-49)	-57(-71)	-43(-46)	-48.5(-55)	-59(-74)	-72
									-40(-41)	-44(-47)	-41(-42)	-56(-68)	-39(-39)	-46.5(-52)	-57(-71)	-74

with varying altitudes.

8

upplemental at atmospheres.)

30° N July,[b] °C (°F)	45° N January,[b] °C (°F)	45° N July,[b] °C (°F)	Mid-latitude spring/fall,[c] °C (°F)	60° N January,[b] °C (°F)	60° N January (cold),[b] °C (°F)	60° N January (warm),[b] °C (°F)	60° N July,[b] °C (°F)	75° N January,[b] °C (°F)	75° N January (cold),[b] °C (°F)	75° N January (warm),[b] °C (°F)	75° N July,[b] °C (°F)
1(89)	0(31)	23(74)	15(59)	-16(3)	-16(3)	-16(3)	15(60)	-24(-11)	-24(-11)	-24(-11)	6(42)
2(72)	-4(25)	18(64)	8.5(47)	-14(7)	-14(7)	-14(7)	10(49)	-21(-6)	-21(-6)	-21(-6)	3(37)
6(62)	-8(18)	13(55)	2(36)	-17(1)	-17(1)	-17(1)	4(39)	-22(-8)	-22(-8)	-22(-8)	0(33)
(40)	-17(1)	0(33)	-11(12)	-25(-14)	-25(-14)	-25(-14)	-7(19)	-33(-28)	-33(-28)	-33(-28)	-11(12)
(20)	-29(-21)	-12(11)	-24(-11)	-39(-38)	-39(-38)	-39(-38)	-20(-4)	-44(-48)	-44(-48)	-44(-48)	-24(-12)
1(-6)	-41(-43)	-25(-13)	-37(-35)	-53(-62)	-53(-63)	-53(-63)	-34(-29)	-55(-67)	-55(-67)	-55(-67)	-37(-35)
5(-31)	-53.5(-64)	-38(-36)	-50(-58)	-56(-69)	-56(-69)	-53(-63)	-48(-54)	-59(-74)	-60(-76)	-54(-65)	-46(-52)
			-56.5(-69.7)								
9(-56)	-54.5(-66)	-51(-60)	-56.5(-69.7)	-56(-69)	-56(-69)	-49(-56)	-48(-54)	-60(-76)	-63(-82)	-51(-60)	-44.5(-48)
3(-81)	-55.5(-68)	-57.5(-72)	-56.5(-69.7)	-56(-69)	-58(-72)	-49(-56)	-48(-54)	-62(-79)	-66(-87)	-51(-60)	-43(-45)
0(-94)	-56.5(-70)	-57.5(-72)	-56.5(-69.7)	-57(-70)	-60(-76)	-49(-56)	-48(-54)	-63(-82)	-69(-93)	-51(-60)	-43(-45)
6(-86)	-57.5(-72)	-56(-69)	-56.5(-69.7)	-58(-72)	-62(-80)	-49(-56)	-48(-54)	-65(-84)	-72(-97)	-50.5(-59)	-43(-45)
1(-78)	-58(-72)	-54(-65)	-56.5(-69.7)	-59(-74)	-64(-83)	-49(-56)	-48(-54)	-65.5(-86)	-73(-99)	-49.5(-57)	-43(-45)
7(-71)	-58(-72)	-51.5(-61)	-54.5(-66)	-60(-76)	-66(-87)	-49(-56)	-48(-54)	-65.5(-86)	-74(-102)	-48.5(-55)	-43(-45)
3(-63)	-58(-72)	-49(-56)	-52.5(-62)	-61(-79)	-68(-90)	-49(-56)	-46(-52)	-65.5(-86)	-75(-104)	-47.5(-54)	-42(-44)
9(-56)	-58(-72)	-47(-52)	-50.5(-59)	-61(-78)	-70(-94)	-48(-55)	-44(-46)	-65.5(-86)	-76(-105)	-45.5(-50)	-40(-40)
5(-49)	-57(-71)	-43(-46)	-48.5(-55)	-59(-74)	-72(-98)	-46(-52)	-40(-41)	-65.5(-86)	-76(-105)	42.5(-44.5)	-38(-36)
1(-42)	-56(-68)	-39(-39)	-46.5(-52)	-57(-71)	-74(-101)	-44(-48)	-38(-36)	-65.5(-86)	-76(-105)	-39.5(-39)	-35(-31)

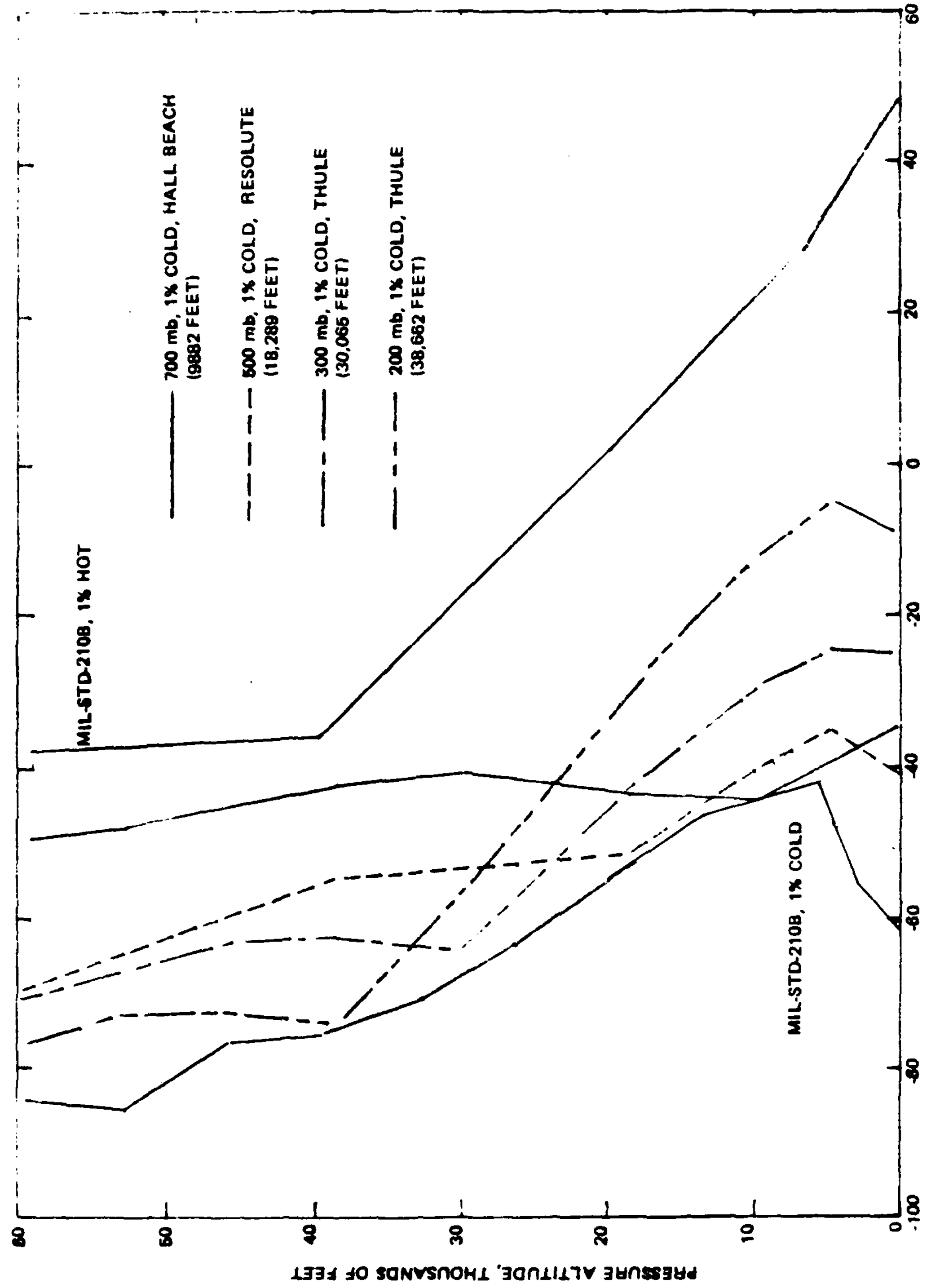

FIGURE 4. Comparison of Cold 1% Temperature Profiles With MIL-STD-210B 1% Atmospheres.

developed in this investigation are shown in Figures 5 and 6. A tabulation of vertically consistent 1% extreme temperature profiles developed for various locations of the world is contained in Table 3. These data are taken directly from the work at the Naval Postgraduate School.[12]

PREFLIGHT ENVIRONMENT

The temperature achieved by a missile in captive flight and subsequent free flight is a strong function of the thermal state of the store at takeoff. This is particularly true for components with large thermal mass such as propulsion systems and warheads and for cases in which flight time is relatively short. The simplest, and often adequate, approach is to use a constant initial temperature. For several years the temperature extremes of -65°F and +160°F were used for storage and preflight conditions. In recent years, NWC has modified these limits, based on analysis and experiment, to the more realistic values of -40°F and +140°F when a constant temperature is desired.

When possible, the expected usage of the system should be considered in the selection of initial temperatures. For example, even the -40°F and +140°F limits are far too extreme for a system that is intended for aircraft carrier operations only. The initial temperatures should be consistent with the model atmosphere being used. Extreme low temperatures at high altitude do not occur at the same time as low temperature extremes at the surface, so it would be more appropriate when analyzing a high altitude, low speed, low temperature soak condition to start at 0°F rather than -40°F. High altitude, high air temperature extremes occur over the Arctic so the 140°F initial temperature would not be appropriate.

Worst case storage conditions could be expected to occur with the missile in open storage. Extreme low temperature conditions at the surface usually occur for a long enough period that the missile soaks to the ambient air temperature. (An atlas of surface temperature extremes has been published.)[14,15] The high temperature storage condition is much more complex. Hot storage conditions are dependent upon geographical location, type of storage, climate, and meteorological conditions. Perhaps the most important store characteristic influencing the store's temperature is the solar absorptivity of the surface coating exposed to the sun. Ideally, all these items are considered in a probabilistic sense as well as a weapon usage sense.

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[14] Paul Tattelman and Arthur J. Kantor. *Atlas of Probabilities of Surface Temperature Extremes: Part I Northern Hemisphere.* 16 April 1976. (AFGL-TR-76-0084, publication UNCLASSIFIED.)

[15] ------. *Atlas of Probabilities of Surface Temperature Extremes Part II Southern Hemisphere* (AFGL-TR-77-0001, publication UNCLASSIFIED.)

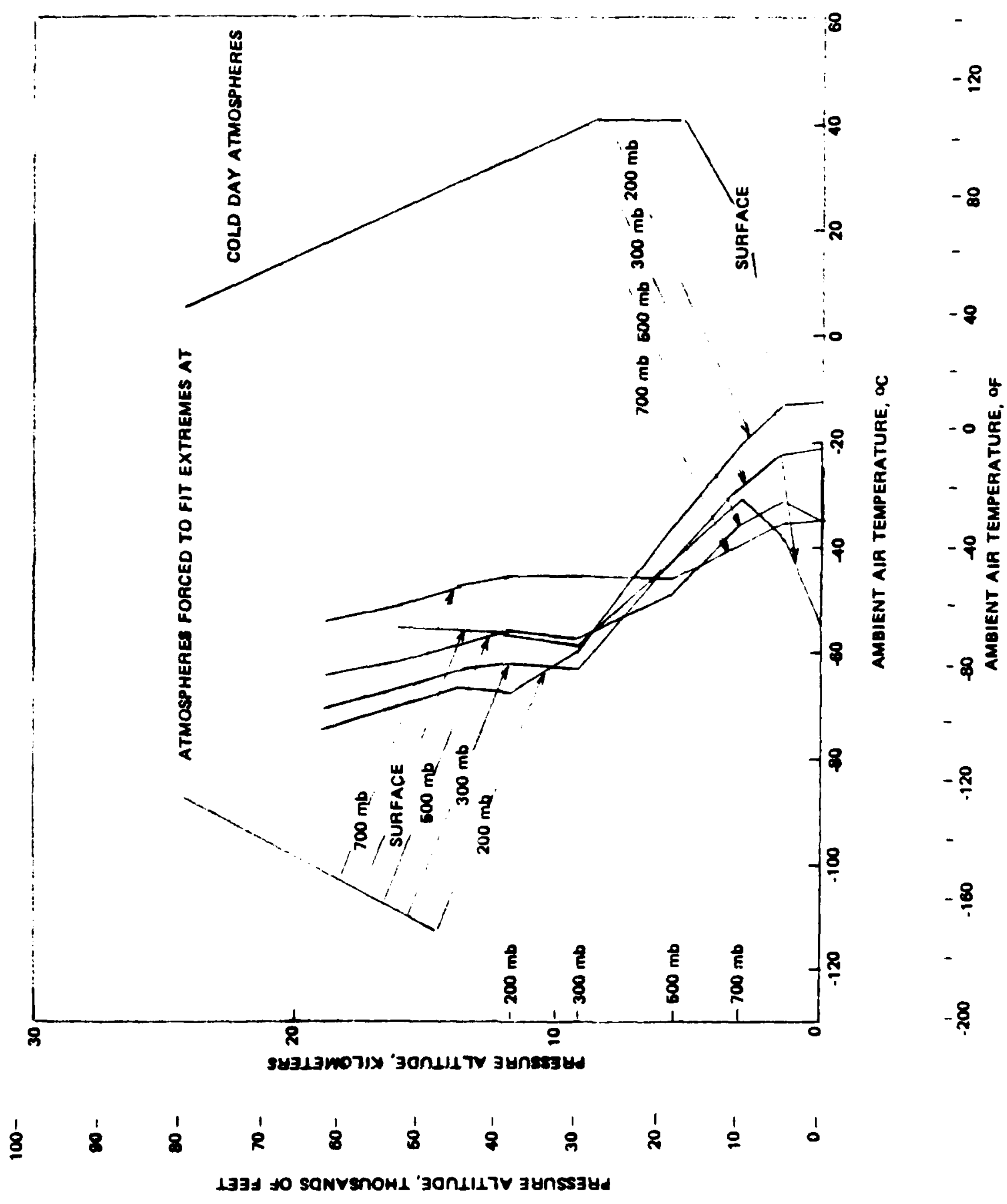

FIGURE 5. Real Cold Atmospheres for Use in Mission Profile Calculations.

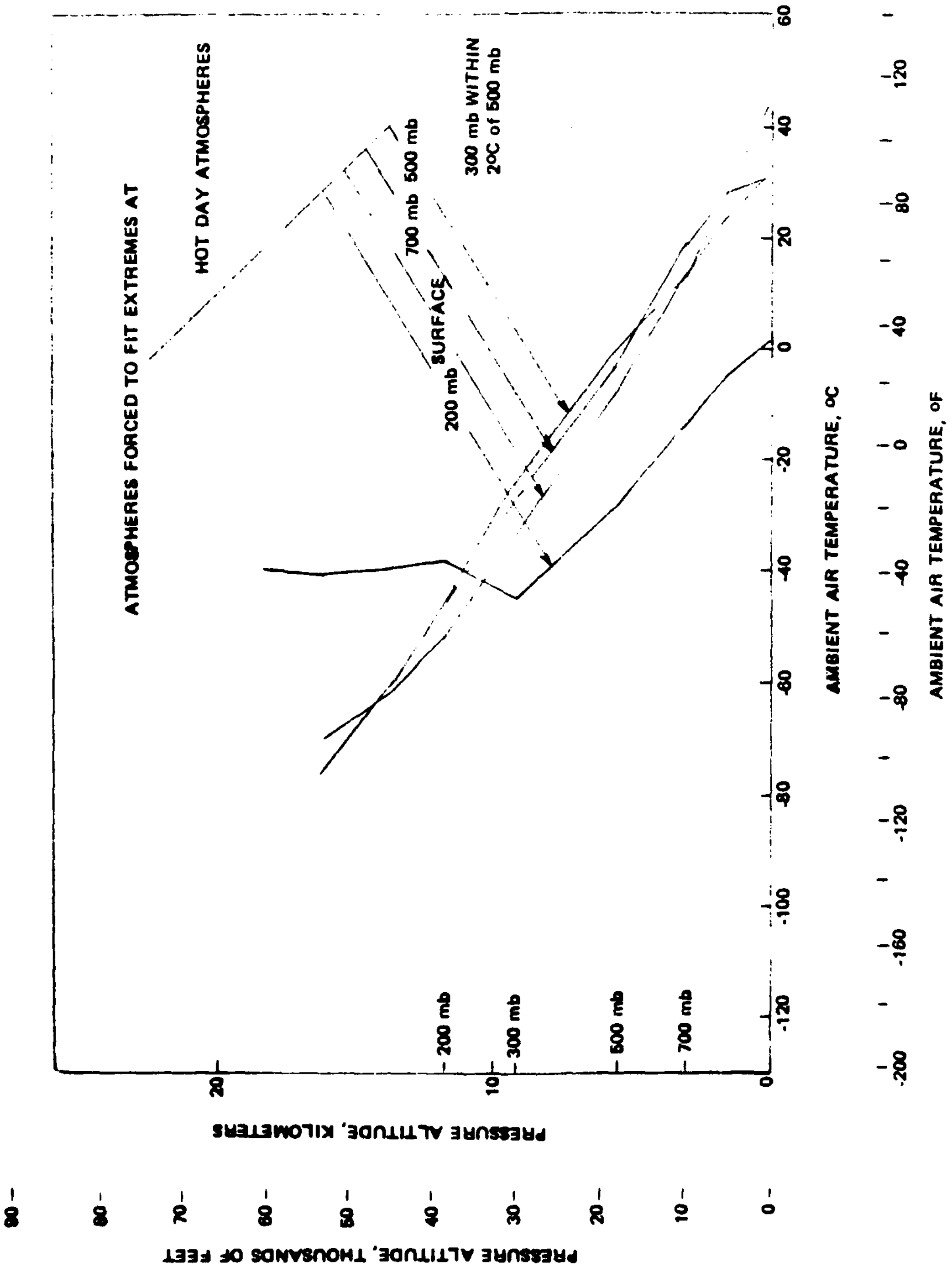

FIGURE 6. Real Hot Atmospheres for Use in Mission Profile Calculations.

TA

Extreme	1% cold	20% cold	1% cold	10% cold	1% cold	10% cold	1% cold	10% cold
Forcing altitude, km	Surface	Surface	1.46	1.46	16.22	16.22	13.62	13.62
Month	January	January	January	January	January	January	January	January
Location	Ojmjakon, USSR	Ojmjakon, USSR	Ojmjakon, USSR	Ojmjakon, USSR	Singapore, Malaysia	Singapore, Malaysia	Singapore, Malaysia	Singapore, Malaysia
Altitude km (feet)								
Surface	-61.3(-78.3)	-55.4(-67.7)	-56.0(-68.8)	-51.2(-60.2)	25.0(77.0)	23.4(74.1)	21.2(70.2)	23.2(73.8)
1.46 (4780)	-35.6(-32.1)	-38.0(-36.4)	-46.7(-52.1)	-43.9(-47.0)	17.6(63.7)	16.9(62.4)	17.6(63.7)	16.9(62.4)
3.01 (9880)	-32.5(-26.5)	-30.7(-23.3)	-32.8(-27.0)	-31.6(-24.9)	8.0(46.4)	8.2(46.8)	8.6(47.5)	7.5(45.5)
5.57 (18,290)	-42.7(-44.9)	-42.0(-43.6)	-41.5(-42.7)	-40.7(-41.3)	-6.8(19.8)	-6.7(19.9)	-4.9(23.2)	-6.9(19.6)
9.36 (30,700)	-60.3(-76.5)	-58.8(-73.8)	-59.8(-75.6)	-57.6(-71.7)	-33.0(-27.4)	-33.2(-27.8)	-32.9(-27.2)	-33.6(-28.5)
11.79 (38,670)	-56.7(-70.1)	-56.6(-69.9)	-56.3(-69.3)	-54.9(-66.8)	-56.6(-69.9)	-55.5(-67.9)	-58.0(-72.4)	-57.4(-71.3)
13.62 (44,690)	-55.4(-67.7)	-55.8(-68.4)	-54.4(-65.9)	-53.9(-65.0)	-70.8(-95.4)	-69.1(-92.4)	-74.3(-101.7)	-72.3(-98.1)
16.22 (53,225)	-54.2(-65.6)	-55.4(-67.7)	-52.7(-62.9)	-52.5(-62.5)	-87.1(-124.8)	-86.0(-122.8)	-82.0(-115.6)	-81.5(-114.7)
Rawinsondes	Twice daily	Twice daily	Twice daily	Twice daily	1200 GMT	1200 GMT	1200 GMT	1200 GMT
Altitude of surface (or altitude used), km	0.726	0.726	0.726	0.726	0.20	0.20	0.20	0.20

[a]F. L. Martin. *Development of Regional Extreme Model Atmospheres for Aerothermodynamic Calculations (II).* Naval Postgraduate School, Monterey

TABLE 3. Vertically Consistent 1% Extreme Temperature Profiles for Various Locations.[a]

(Temperatures in °C (°F))

10% cold	1% cold	10% cold	1% hot	10% hot	1% hot	10% hot	1% hot	10% hot	1% hot	10% hot	1% hot
13.62	13.62	13.62	Surface	Surface	1.46	1.46	Surface	Surface	3.01	3.01	3.01
January	January	January	July	July	July	July	July	July	July	July	July
Singapore, Malaysia	New Delhi, India	New Delhi, India	Insalah, Algeria	Insalah, Algeria	Insalah, Algeria	Insalah, Algeria	Baghdad, Iraq	Baghdad, Iraq	Baghdad, Iraq	Baghdad, Iraq	Baghdad, Iraq
23.2(73.8)	...	...	43.7(110.7)	43.3(109.9)	41.7(107.1)	41.2(106.2)	49.1(120.4)	48.1(118.6)	33.6(92.5)	31.3(88.3)	49.0(120.2)
16.9(62.4)	14.4(57.9)	10.9(51.6)	29.2(84.6)	29.6(85.3)	34.7(94.5)	32.3(90.1)	28.0(82.4)	29.6(85.3)	28.4(83.1)	28.8(83.8)	30.2(86.4)
7.5(45.5)	3.4(38.1)	1.2(34.2)	13.6(56.5)	14.1(57.4)	18.1(64.6)	16.5(61.7)	15.6(60.1)	16.5(61.7)	20.6(69.1)	19.3(66.7)	19.7(67.5)
-6.9(19.6)	-12.9(8.8)	-14.6(5.7)	-7.6(18.3)	-7.6(18.3)	-4.6(23.7)	-6.0(21.2)	-1.6(29.1)	-1.3(29.7)	-4.8(23.4)	-2.4(27.7)	0.2(32.4)
33.6(-28.5)	-42.0(-43.6)	-37.3(-35.1)	-33.0(-27.4)	-33.1(-27.6)	-26.2(-15.2)	-30.0(-22.0)	-26.5(-15.7)	-26.6(-15.9)	-25.7(-14.3)	-26.6(-15.9)	-25.5(-13.9)
57.4(-71.3)	-58.1(-72.6)	-55.5(-67.9)	-52.6(-62.7)	-51.1(-60.0)	-44.1(-47.4)	-47.6(-53.7)	-44.8(-48.6)	-45.4(-49.7)	-46.4(-51.5)	-46.1(-51.0)	-44.2(-47.6)
72.3(-98.1)	-70.7(-95.3)	-68.3(-90.9)	-63.8(-82.8)	-61.5(-78.7)	-55.0(-67.0)	-56.9(-70.4)	-56.8(-70.2)	-57.8(-72.0)	-60.3(-76.5)	-59.7(-75.5)	-56.5(-69.7)
81.5(-114.7)	-71.6(-96.9)	-74.5(-102.1)	-71.4(-96.5)	-69.7(-93.5)	-64.4(-83.9)	-66.5(-87.7)	-69.2(-92.6)	-71.8(-97.2)	-77.2(-107.0)	-75.5(-103.9)	-70.8(-95.4)
1200 GMT			1200 GMT	1200 GMT	1200 GMT	1200 GMT	1200 GMT	1200 GMT	0000 GMT	0000 GMT	1200 GMT
0.20	...	...	0.28	0.28	0.28	0.28	0.15	0.15	0.15	0.15	0.15

School, Monterey, CA, 1 July 1973.

Locations.[a]

hot	10% hot	1% hot	10% hot	1% hot	10% hot	1% hot	10% hot	1% hot	10% hot
rface	Surface	3.01	3.01	3.01	3.01	5.57	5.57	9.36	9.36
uly	July	July	July	July	July	July	July	July	July
hdad, raq	Baghdad, Iraq	Baghdad, Iraq	Baghdad, Iraq	Baghdad, Iraq	Baghdad, Iraq	New Delhi, India	New Delhi, India	New Delhi, India	New Delhi, India
(120.4)	48.1(118.6)	33.6(92.5)	31.3(88.3)	49.0(120.2)	46.8(116.2)	28.0(82.4)	31.6(88.9)	27.6(81.7)	31.2(88.2)
(82.4)	29.6(85.3)	28.4(83.1)	28.8(83.8)	30.2(86.4)	30.7(87.3)	22.7(72.9)	24.4(75.9)	24.3(75.7)	24.7(76.5)
(60.1)	16.5(61.7)	20.6(69.1)	19.3(66.7)	19.7(67.5)	18.6(65.5)	13.7(56.7)	13.4(56.1)	14.3(57.7)	14.2(57.6)
(29.1)	-1.3(29.7)	-4.8(23.4)	-2.4(27.7)	0.2(32.4)	-3.7(25.3)	1.2(34.2)	0.5(32.9)	-0.6(30.9)	-0.4(31.3)
(-15.7)	-26.6(-15.9)	-25.7(-14.3)	-26.6(-15.9)	-25.5(-13.9)	-26.6(-15.9)	-34.8(-30.6)	-23.7(-10.7)	-20.6(-5.1)	-22.0(-7.6)
(-48.6)	-45.4(-49.7)	-46.4(-51.5)	-46.1(-51.0)	-44.2(-47.6)	-44.6(-48.3)	-49.3(-56.7)	-45.6(-50.1)	-41.8(-43.2)	-43.5(-46.3)
(-70.2)	-57.8(-72.0)	-60.3(-76.5)	-59.7(-75.5)	-56.5(-69.7)	-56.6(-69.9)	-65.7(-86.3)	-60.4(-76.7)	-56.8(-70.2)	-58.3(-72.9)
(-92.6)	-71.8(-97.2)	-77.2(-107.0)	-75.5(-103.9)	-70.8(-95.4)	-71.7(-97.1)	-79.6(-111.3)	-75.1(-103.2)	-75.4(-103.7)	-74.9(-102.8)
200 MT	1200 GMT	0000 GMT	0000 GMT	1200 GMT	1200 GMT	Twice daily	Twice daily	Twice daily	Twice daily
.15	0.15	0.15	0.15	0.15	0.15	0.22	0.22	0.22	0.22

The storage problem is actually a very complex analytical problem and has been considered in many investigations at NWC.[16-20] It has been possible, however, to develop a relatively simple calculative technique for predicting the temperature of a store as a function of time of day. This technique has been verified by experiment.[21] Briefly, the method involves an energy balance between the solar radiation, the long-wavelength radiation exchange with the atmosphere and surroundings, and the convective heat transfer between the body and the air. The amount of incident radiation absorbed by the body is controlled by the solar absorptivity, which is dependent on the surface properties. It is particularly difficult to assign an accurate value to this parameter.

The energy balance may be represented by the following equation:

$$\alpha_L q_{atm} + \alpha_s q_{solar} + h(T_r - T_{skin}) = \sigma\epsilon T^4_{skin}$$

where

$\alpha_L q_{atm}$	=	atmospheric radiation
$\alpha_s q_{solar}$	=	solar radiation
$h(T_r - T_{skin})$	=	convective heat transfer
$\sigma\epsilon T^4_{skin}$	=	heat output due to radiation

Details of these definitions may be found in the Nomenclature.

The solar absorptivity, α_s, is available for some materials and finishes but varies with age, condition, and other undefinable factors. The heat transfer coefficient, h, can be calculated by conventional techniques and is used as an average local value which is dependent upon wind speed. Minimum wind is assumed in order to obtain the extreme conditions. The value is usually 2 to 3 Btu/ft^2-hr-°F. The atmospheric radiation, q_{atm}, is assumed to be a

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[16] Naval Weapons Center. *Computer Prediction of Ordnance Storage Temperature*, by C. L. Markarian. China Lake, CA, NWC, 24 February 1976. (NWC Memo Reg. 4061-8-76, publication UNCLASSIFIED.)

[17] ------. *Thermal Modeling of a Missile/Missile Container System*, by M. L. Lee (Fung). China Lake, CA, NWC, 30 January 1973. (NWC Memo Reg. 4061-29-73, publication UNCLASSIFIED.)

[18] ------. *Evolution of the NWC Thermal Standard, Part 3. Application and Evaluation of the Thermal Standard in the Field*, by R. D. Ulrich and H. C. Schafer. China Lake, CA, NWC, May 1977. (NWC TP 4834, publication UNCLASSIFIED.)

[19] ------. *HARM Storage Temperatures*, by B. M. Ryan. China Lake, CA, NWC, 4 March 1977. (NWC Memo Reg. 3161-6a-77, publication UNCLASSIFIED.)

[20] ------. *Effect of Paint Color on Sidewinder Temperatures*, by B. M. Ryan. China Lake, CA, NWC, 5 August 1977. (NWC Memo Reg. 3161-48-77, publication UNCLASSIFIED.)

[21] ------. *Temperature of Sidewinder (AIM-9L) Missile in Open Desert Storage*, by M. D. Herr and B. M. Ryan. China Lake, CA, NWC, September 1979. (NWC TM 4024, publication UNCLASSIFIED.)

function of the ambient air temperature plus 30 F ($q_{atm} = \sigma(T + 30)^4$, where σ is the Stefan-Boltzman constant and the temperature, T, is in absolute units). Other more sophisticated relations have been assumed for q_{atm} but this simple one has proven adequate.

The diurnal variation of solar radiation, ambient air temperature, and wind speed are taken from MIL-STD-210B (footnote 10, Table I, p. 45). When comparisons with experiment are made (as has been done to verify the techniques), the actual values for the day are used in the computation. For the extreme temperature calculation, the 1% risk is used for two reasons:

1. The calculation has many uncertainties, so an extreme atmosphere is used to partially compensate.

2. Storage usually takes place over a comparatively long elapsed time, so there is more opportunity for encountering the low percentage risk.

The 1% risk values of ambient air temperature and solar radiation as a function of time of day are shown in Figure 7 and listed in Table 4. There is some argument as to the legitimacy of using extremes of both temperature and solar radiation in the same calculation, since they do not necessarily occur simultaneously.

In addition to the simplifying assumptions described above, the calculation is one-dimensional. No sun angles are assumed for heating variations, and missile exposed areas are adjusted to compensate for the one-dimensional analysis. The results of an analysis using MIL-STD-210B diurnal temperature and solar radiation variations are shown in Figure 8. The maximum skin temperature reached by the gray painted item is about 165°F and by the white painted item, about 125°F. Due to the thermal masses and slow heating variations, the maximum temperatures vary insignificantly for various missile components. The shape of the curve and the maximum temperatures achieved also vary insignificantly over a 3-day period.

Extensive experimental temperature measurements and calculations for an air-to-air missile in open storage have been reported (footnote 21). In selecting a day to compare with experiment one would tend to choose a cloudless day with minimum wind and low humidity. Two such comparisons are shown in Figure 9 for two different days when the maximum solar radiation was about 300 Btu/ft^2-hr and the maximum ambient air temperature was 108°F on one day and 93°F on the second day. In view of the simplifying assumption made in the analysis, the agreement is quite good. Comparisons of this type also serve to validate the analytical model.

Experimental data have shown the surface on (or over) which the missile is stored has negligible influence on the temperature. When a missile is mounted under an aircraft wing, the effects may be less severe since the aircraft wing may shade the missile during part of the day. Wing-tip-mounted missiles, however, might be continuously exposed to the sun. Also, of course, open storage is more severe than any kind of covered storage (unless a white missile is stored in a gray container or building).

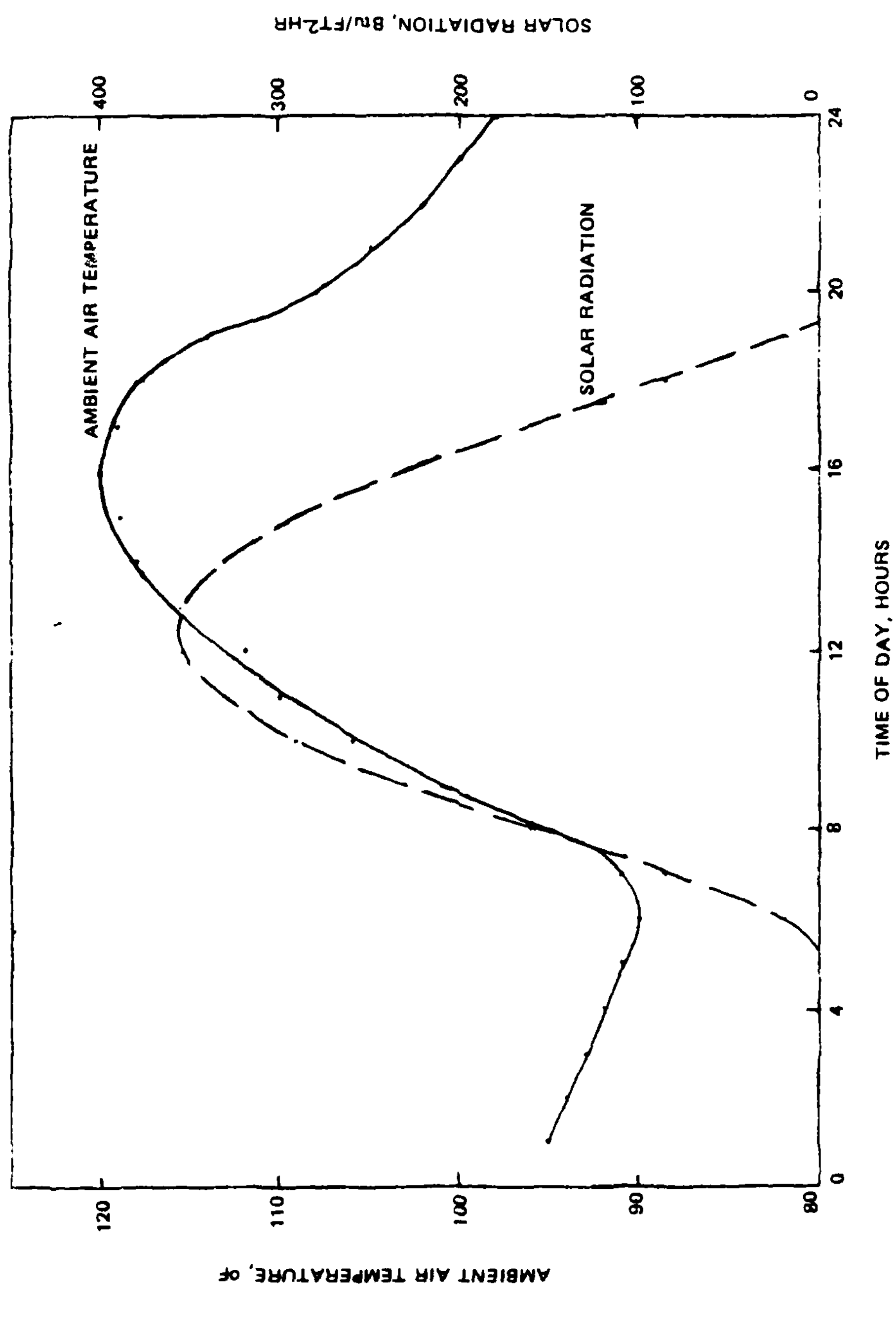

FIGURE 7. Ambient Air Temperature and Solar Radiation Used in Storage Calculations.

TABLE 4. MIL-STD-210B 1% Risk Values of Diurnal Variation of Ambient Air Temperature and Solar Radiation.

Time of day, hours	Ambient air temperature, °F (°C)	Solar radiation, Btu/hr ft^2 (Lph)
01	95 (35)	0 (0)
02	94 (34)	0 (0)
03	93 (34)	0 (0)
04	92 (33)	0 (0)
05	91 (33)	0 (0)
06	90 (32)	18 (5)
07	91 (33)	85 (23)
08	95 (35)	160 (43)
09	101 (38)	231 (63)
10	106 (41)	291 (79)
11	110 (43)	330 (90)
12	112 (44)	355 (96)
13	116 (47)	355 (96)
14	118 (48)	330 (90)
15	119 (48)	291 (79)
16	120 (49)	231 (63)
17	119 (48)	160 (43)
18	118 (48)	85 (23)
19	114 (46)	18 (5)
20	108 (42)	0 (0)
21	105 (41)	0 (0)
22	102 (39)	0 (0)
23	100 (38)	0 (0)
24	98 (37)	0 (0)

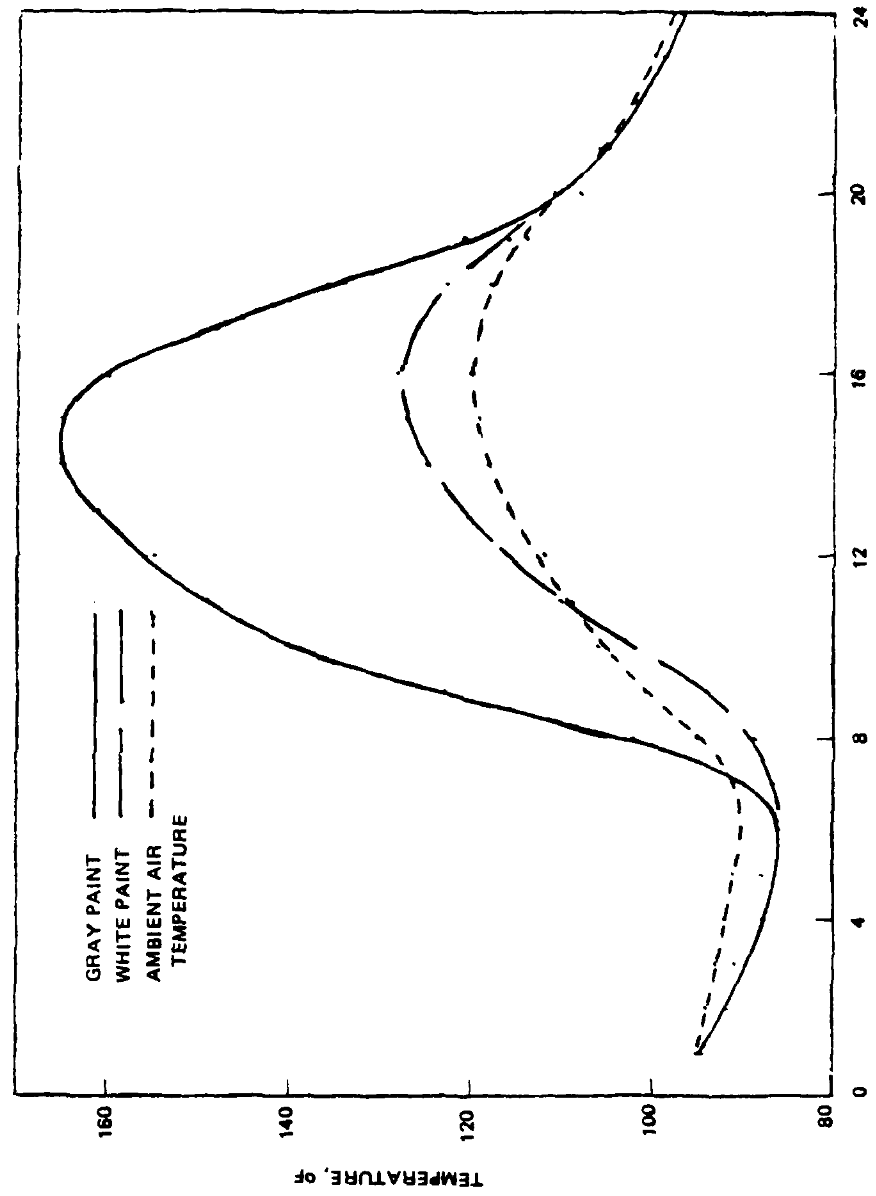

FIGURE 8. Calculated Skin Temperatures Achieved in Open Storage on a 1% Hot Day.

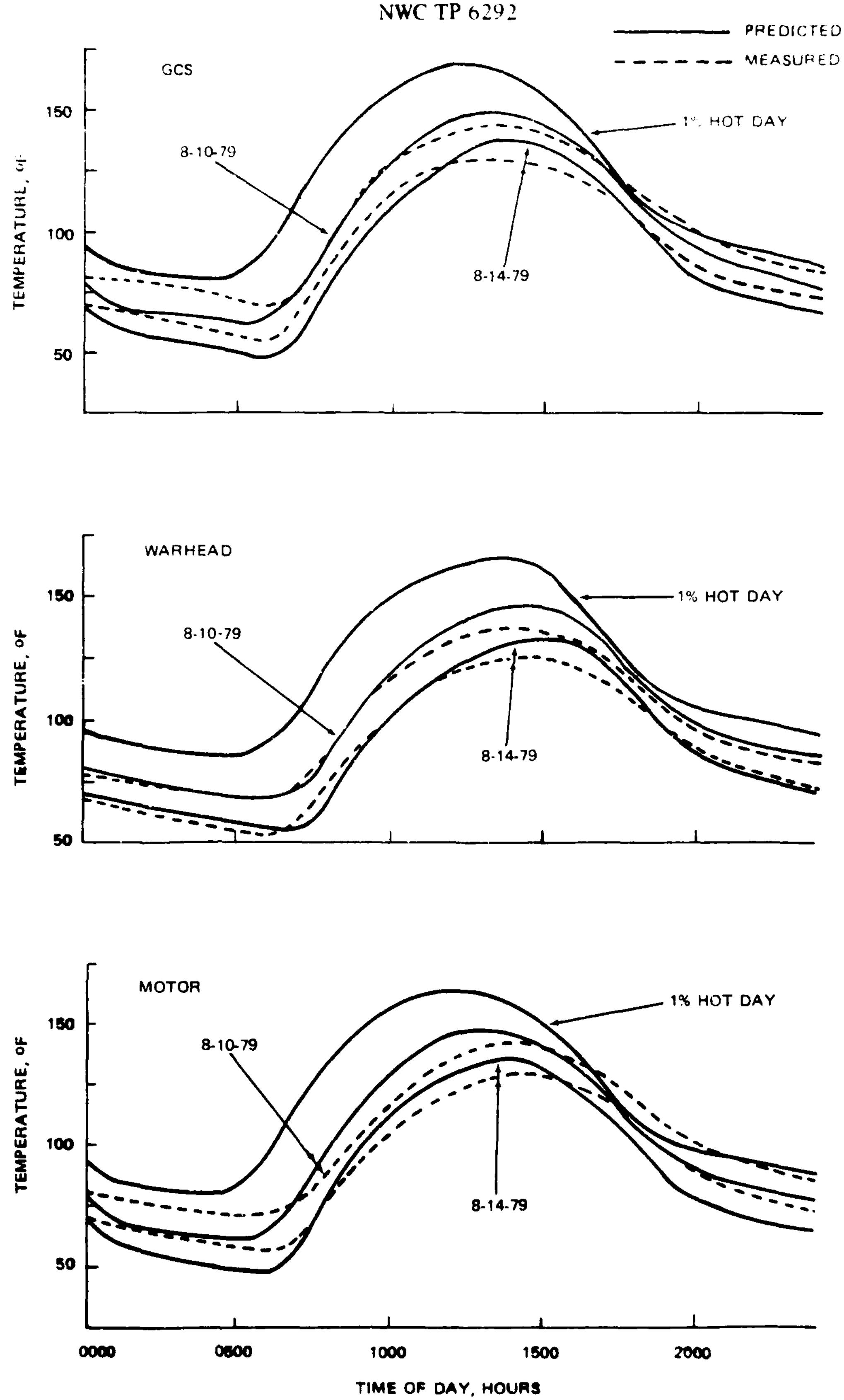

FIGURE 9. Measured and Calculated Storage Temperatures.

In summary, the initial hot soak temperature for a captive flight missile is assumed to be 130°F. This temperature is not the maximum achievable but is believed to be a realistic extreme due to the rarity of the 1% hot day combined with extreme storage conditions and the time involved for a complete soak of the missile. For the cold extreme, a temperature soak is selected which is similar to the minimum ambient air temperature that is consistent with the ground level temperature of the atmospheric profile being used for the captive flight thermal calculations.

CAPTIVE FLIGHT ENVIRONMENT

The captive carry portion of the life cycle of a weapon system is a most important phase in the thermal exposure of the weapon. Yet probably the greatest uncertainties in the determination of aerothermal environments are in the definition of a realistic flight environment while the missile is being carried aboard an aircraft. The extreme conditions are represented by the operational envelope of the aircraft of interest in a clean configuration (no stores). This envelope gives the maximum and minimum Mach numbers as a function of altitude. Recovery temperatures computed from the envelope using the MIL-STD-210B hot and cold ambient air temperatures will represent the thermal extremes experienced by the missile in captive flight. Although this is a simple way of estimating the captive flight temperature envelope of the missile, the values can be considerably more extreme than those experienced in actual use. The drag and weight of external stores have a major effect on the aircraft performance envelope, as does the atmospheric temperature. The effect of temperature on maximum Mach number can be such that at high altitudes, higher recovery temperatures will occur under cold atmosphere conditions than under hot conditions. All of these circumstances as well as the design mission of the weapon system must be considered in the selection of a captive flight environment from which to calculate the thermal state of the store at launch.

A convenient technique for estimating the extreme temperatures a store might experience is to calculate the recovery temperature based on turbulent flow conditions. This temperature is the equilibrium temperature that would eventually be achieved due to aerodynamic heating only; that is, in the absence of radiation and active heating or cooling. Radiation effects are negligible in the typical captive flight condition. Captive flight times are long enough that, except for maximum Mach number flight, it is not unreasonable to assume the skin of the store can reach recovery temperature. The internal response of the store, however, would lag recovery (or skin) temperature in a way dependent upon the thermal characteristics of the store. In its simplest form, recovery temperature is a function of Mach number and altitude (ambient air temperature) only and is the temperature that the skin would approach asymptotically if Mach number and altitude conditions were maintained long enough:

$$T_r = T_\infty (1 + 0.178 M^2)$$

where M is the Mach number and T_∞ is the ambient air temperature (in degrees Rankine or Kelvin) at the particular altitude. Thus the recovery temperature, T_r, is known in terms of the flight profile only when the atmosphere is known. For convenience, recovery temperature as a function of altitude and Mach number is presented in Figures 10, 11, and 12. Three atmospheres are used, the standard (Figure 10), the 10% cold (Figure 11), and the 10% hot (Figure 12). It should be kept in mind that the atmospheres used for Figures 11 and 12 are envelopes of extremes.

A recovery temperature envelope that might be generated for a missile carried on board a typical fighter aircraft is shown in Figure 13. The curves on the right represent the design speed limit. The curves on the left represent the $C_{L_{max}}$ (near stall) condition at the lower altitudes and the engine limit at the higher altitudes. The horizontal dashed line is the clean, no fuel service ceiling. The various lines as labeled are recovery temperature values for the standard atmosphere and envelopes of recovery temperatures for MIL-STD-210B 10% risk hot and cold day extremes. Using this graph the designer might think it necessary to design the missile to be carried on this aircraft for temperature extremes between -75°F and +450°F. But further consideration should be given to the practicality of these numbers as well as the probability of occurrence.

The performance figures shown in Figure 13 are the maximum performance data from the airplane manual. The effect on performance due to the additional weight and drag of stores is not considered. As an obvious example of an unrealistic condition, the service ceiling of a clean aircraft with no fuel represents a situation not encountered in real life. The atmosphere also has a direct effect on performance, and extreme atmospheric temperatures will modify the performance of the aircraft so should not be applied to standard day performance figures. Also not included in Figure 13 is the effect of time, which is dependent on fuel load, mission, tactics, etc. The recovery temperature can represent the maximum skin temperature, but the internal temperatures are dependent on the configuration and material properties of the store and the time required to transfer the heat internally. Aircraft spend very little of their lifetime at or near the boundaries of their operational envelope. When this fact is combined with the percentage risk of the MIL-STD-210B atmospheric temperatures, the probability of occurrence of the extreme recovery temperatures becomes exceedingly low. It might seem appropriate to design to these extremes for added conservatism, but, with the exception of explosive and propulsion components, the failure of which could cause loss of life, the penalties for overdesign are excessive. It has been estimated that the cost of electronics systems doubles for every 10°F below 0°F in desired capability. Likewise, a difference of a few degrees in maximum design temperature can mean the difference between no insulation requirements, an external thermal insulation, passive cooling (heat pipes), or a complex and expensive active cooling system. Also, higher design temperatures mean more exotic, high-cost materials.

The effect of stores on maximum speed recovery temperatures is shown in Figure 14 for a typical fighter aircraft flying in standard day conditions. The clean aircraft can reach speeds that could generate skin temperatures of about 275°F if maintained for a long enough time. Adding missiles, part of a fighter's combat equipment, reduces this temperature to

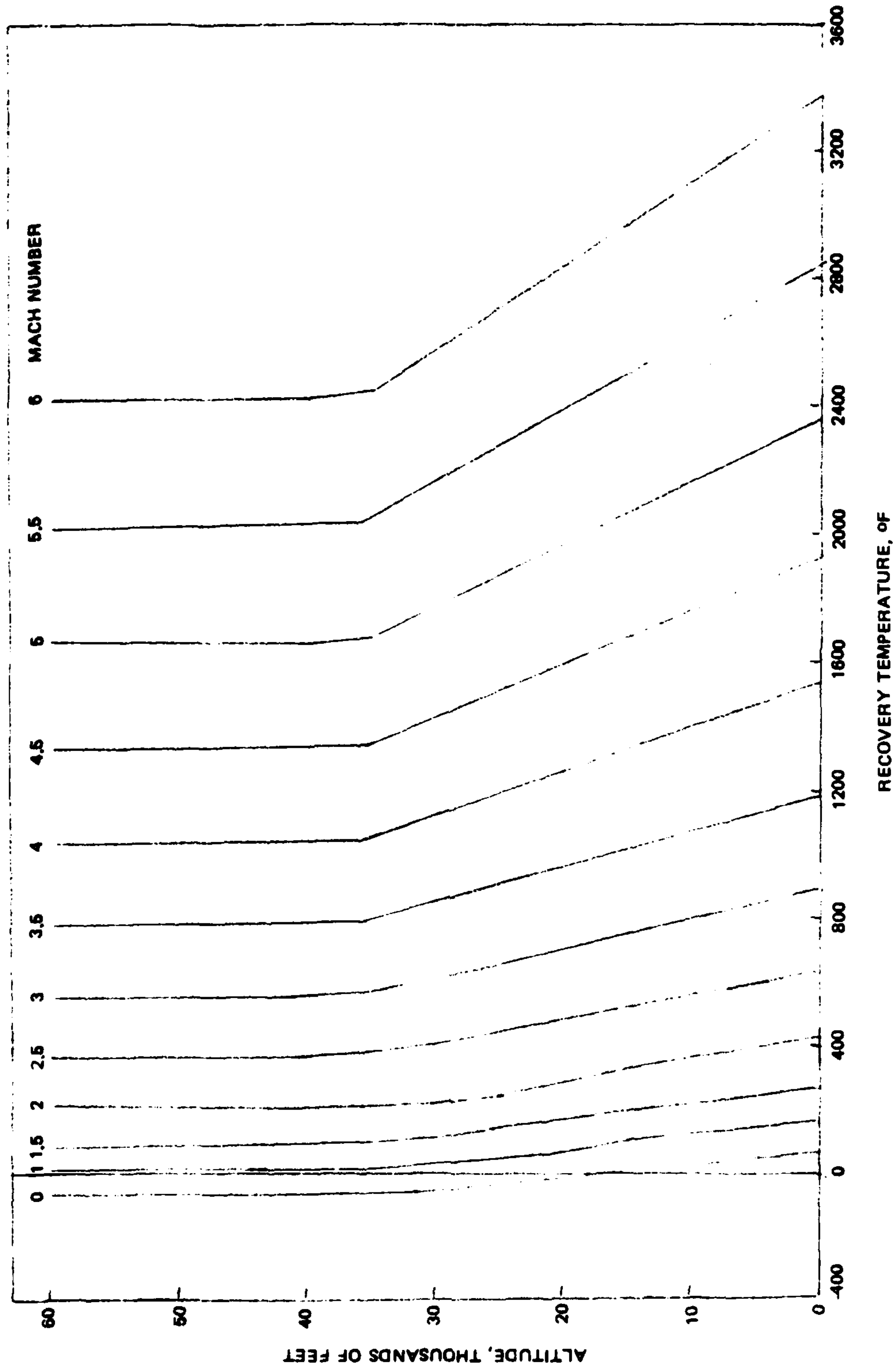

FIGURE 10. Recovery Temperature as a Function of Altitude for Several Mach Numbers - Standard Day.

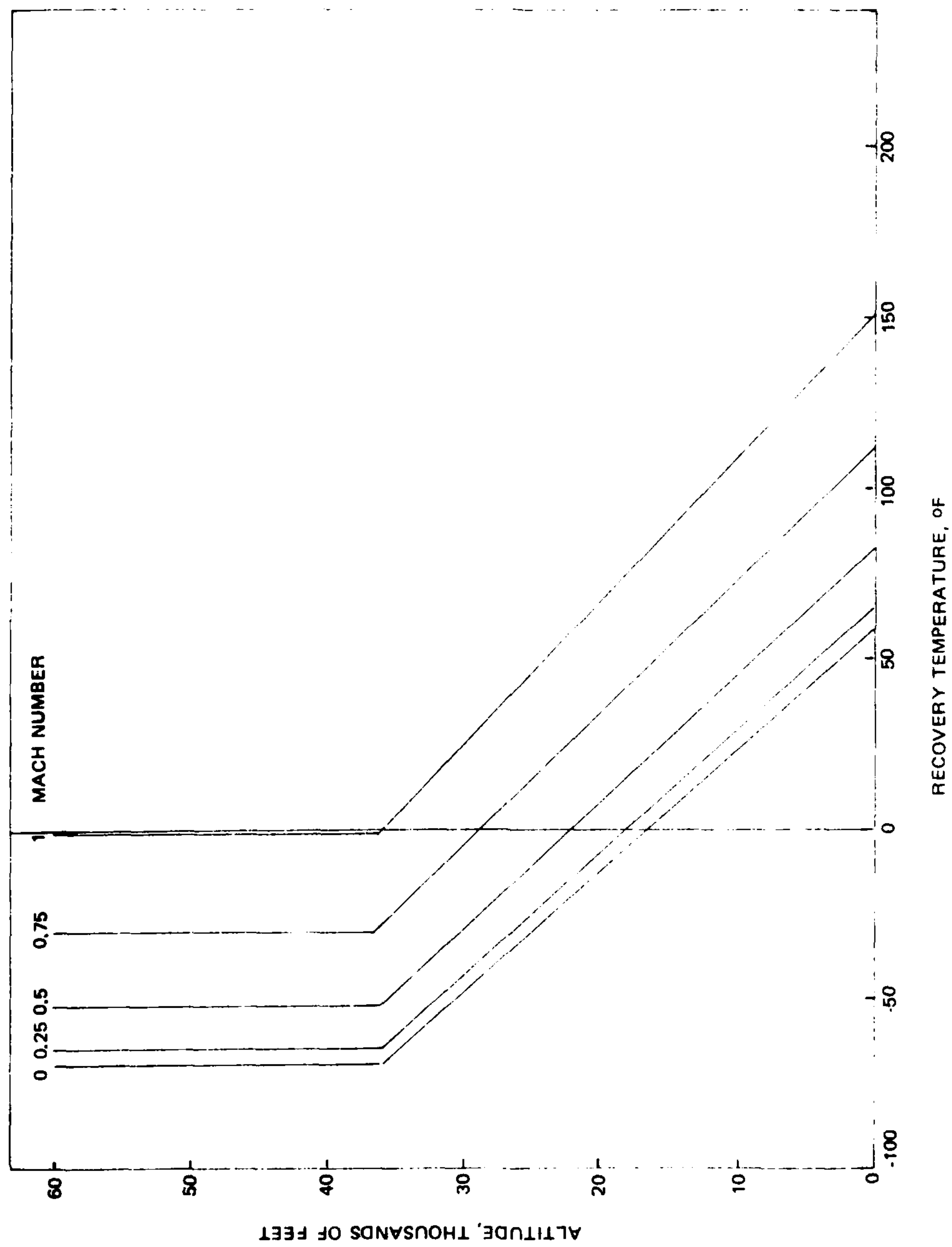

FIGURE 10. (Contd.)

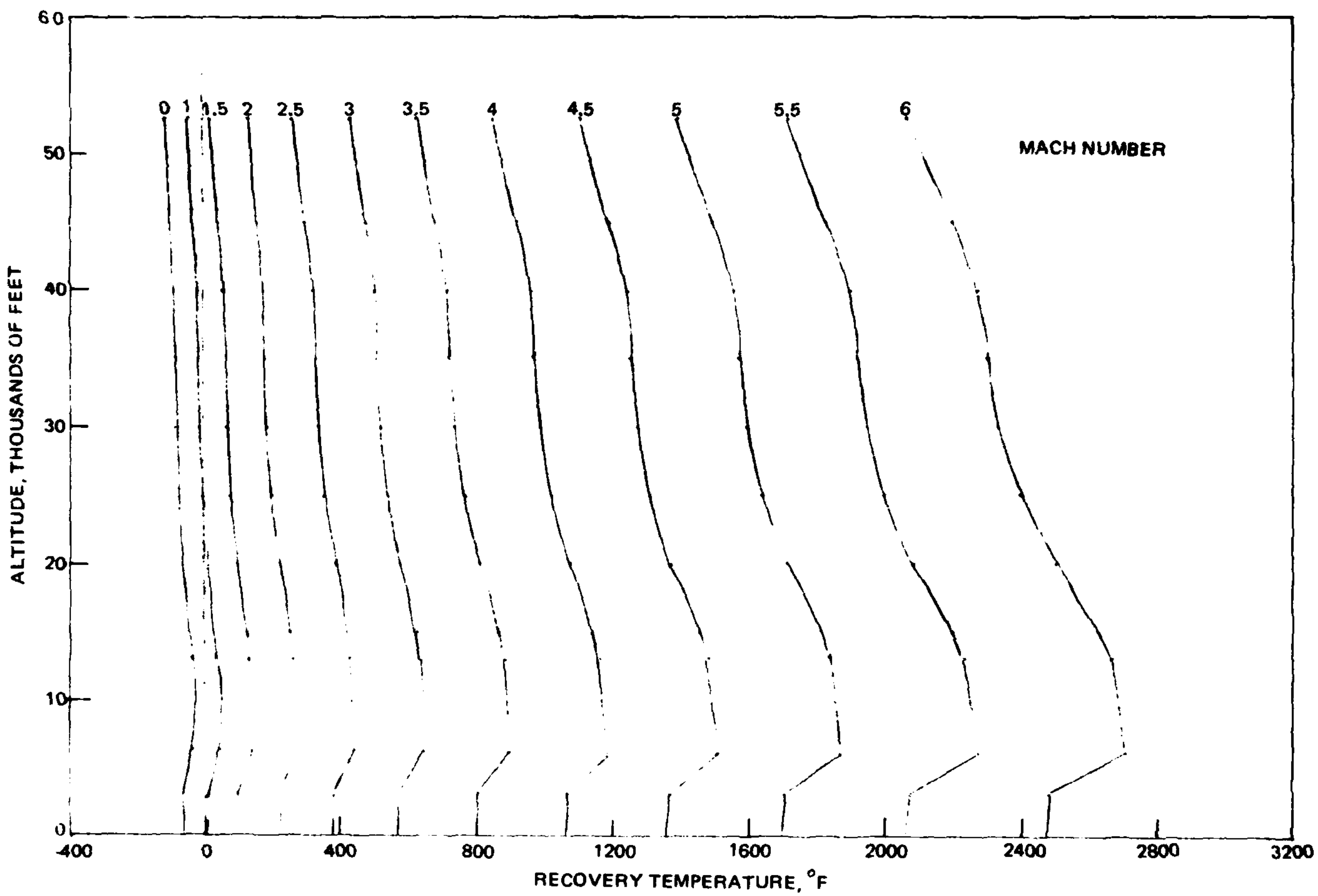

FIGURE 11. Recovery Temperature as a Function of Altitude for Several Mach Numbers - MIL-STD-210B, 10% Cold Day.

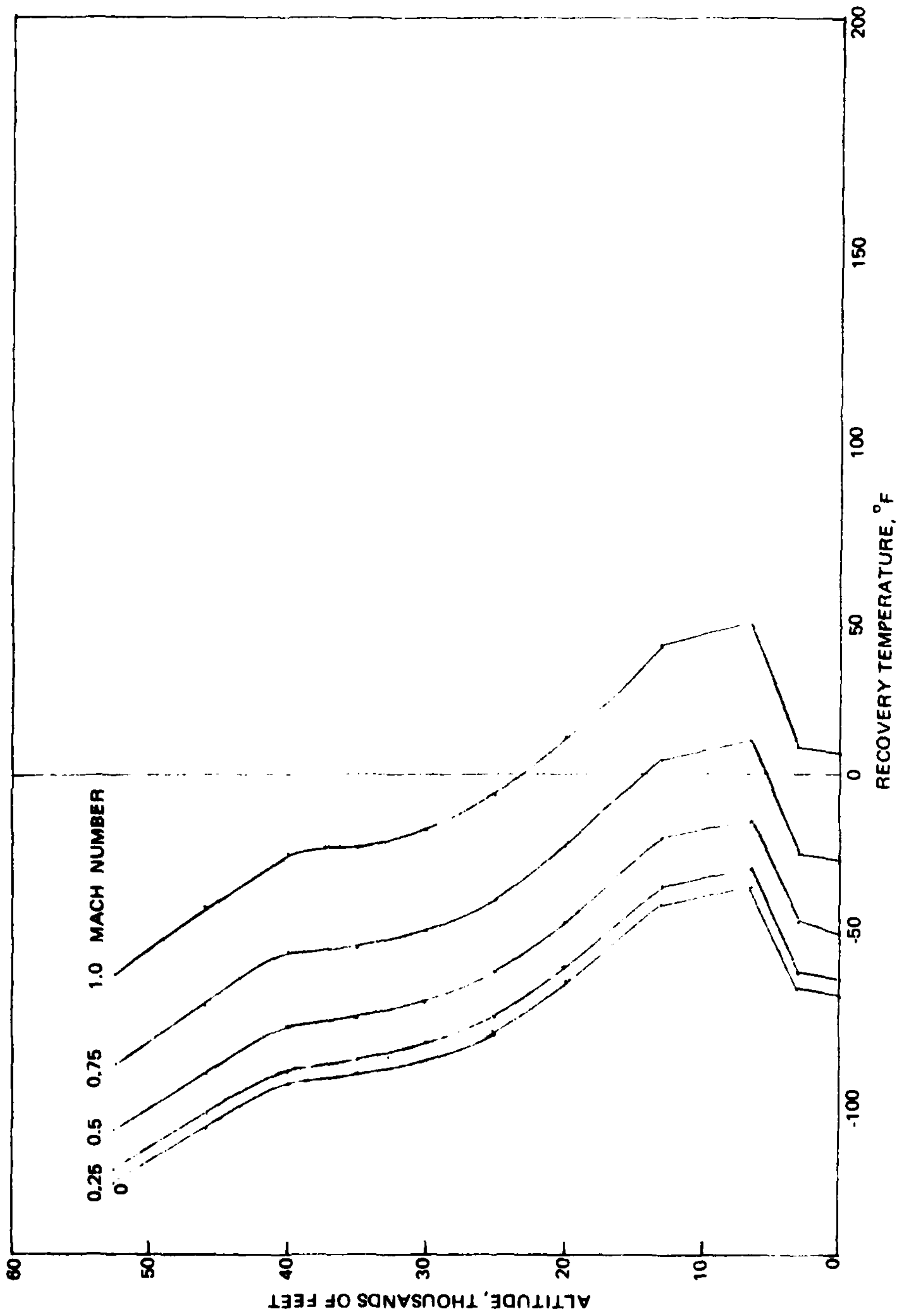

FIGURE 11. (Contd.)

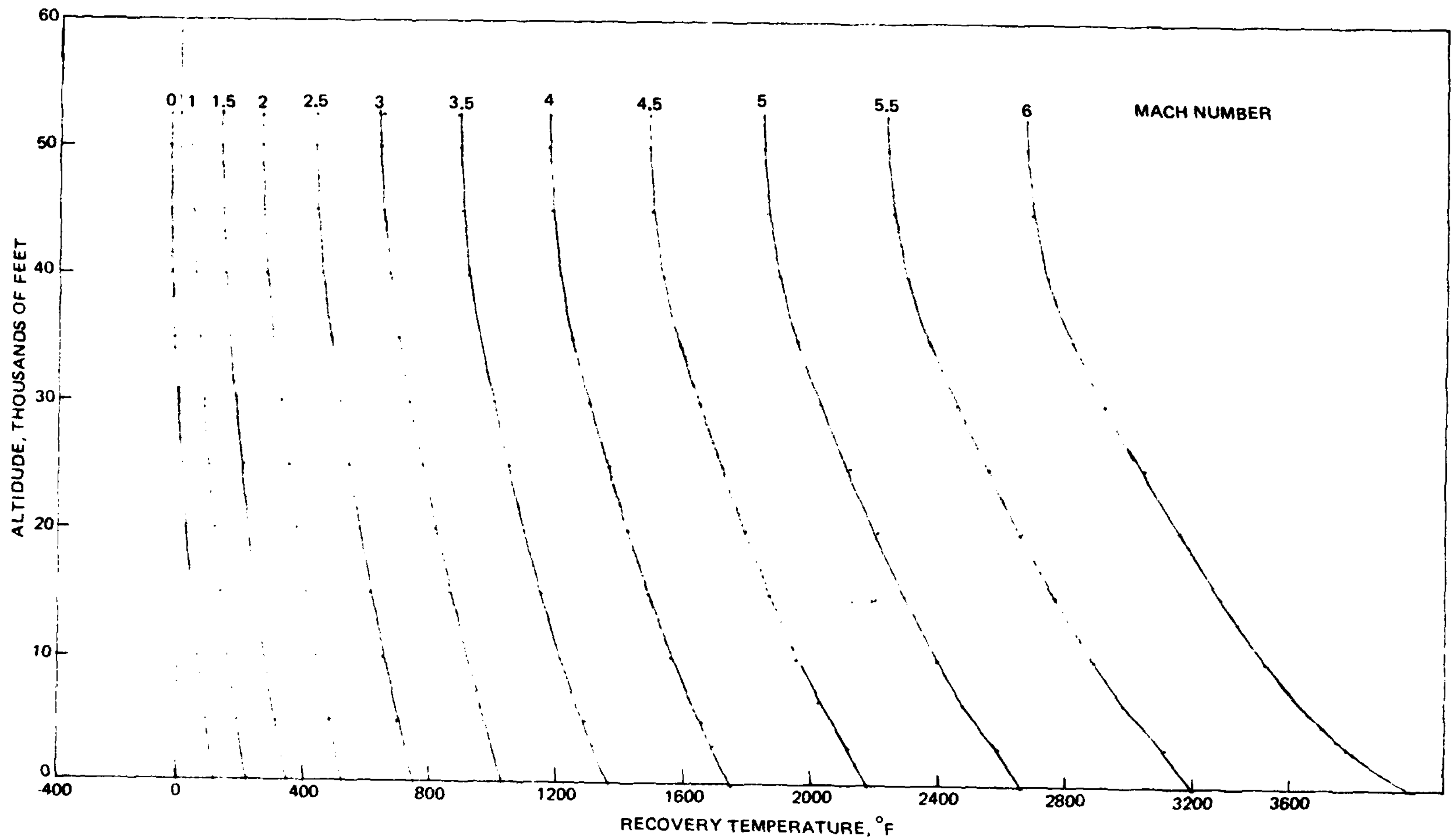

FIGURE 12. Recovery Temperature as a Function of Altitude for Several Mach Numbers - MIL-STD-210B. 10% Hot Day.

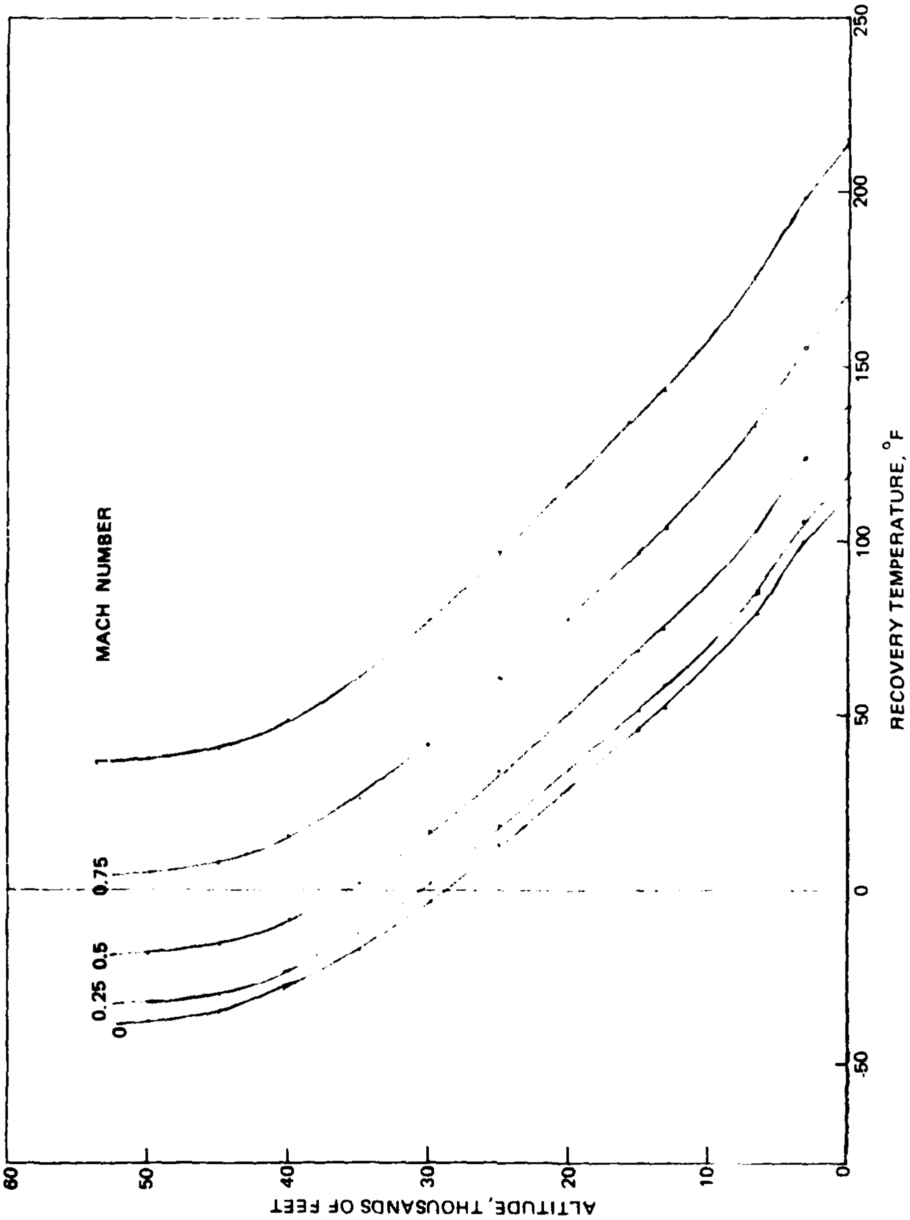

FIGURE 12. (Contd.)

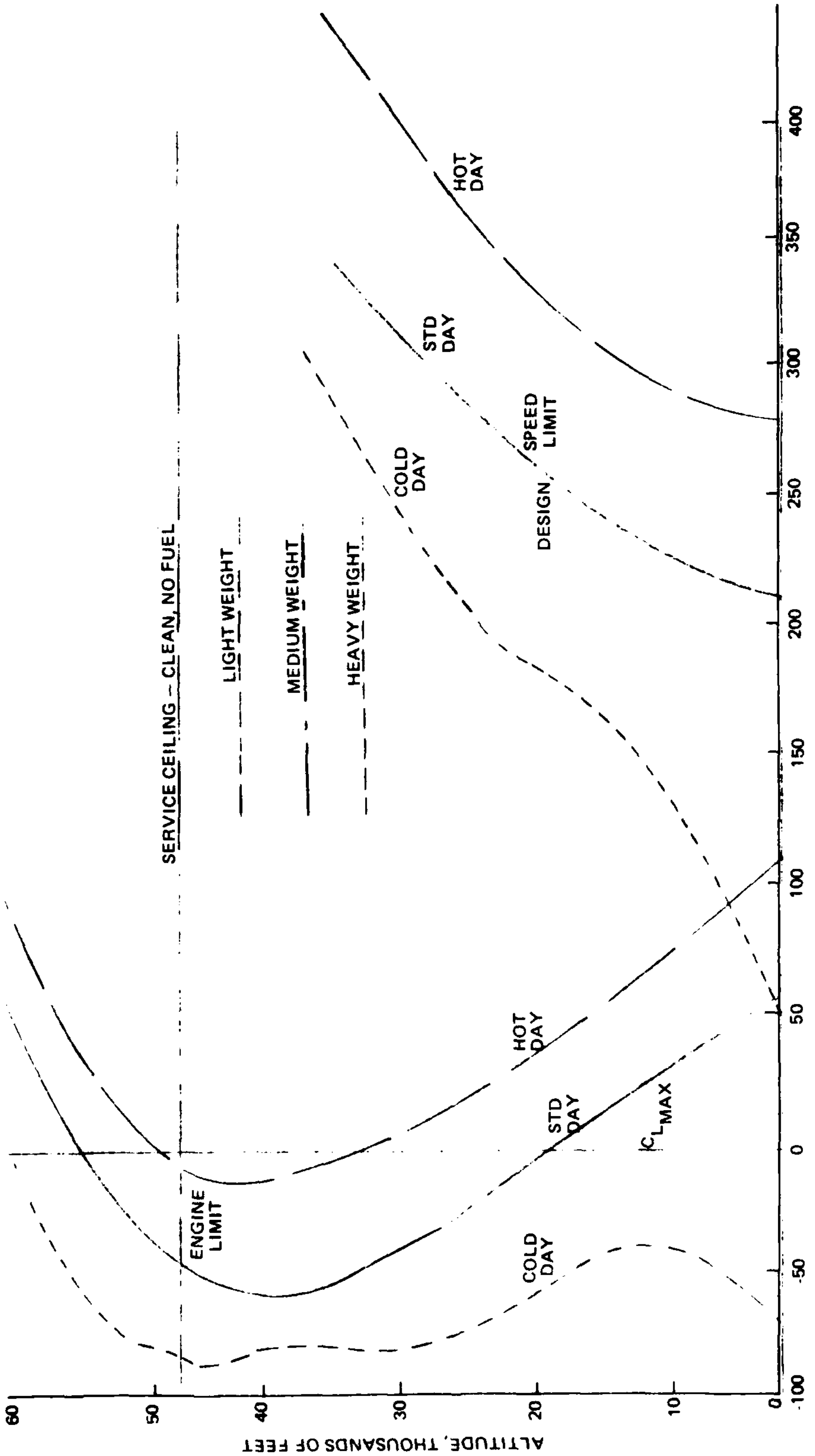

FIGURE 13. Recovery Temperature Envelope for Typical Fighter Aircraft.

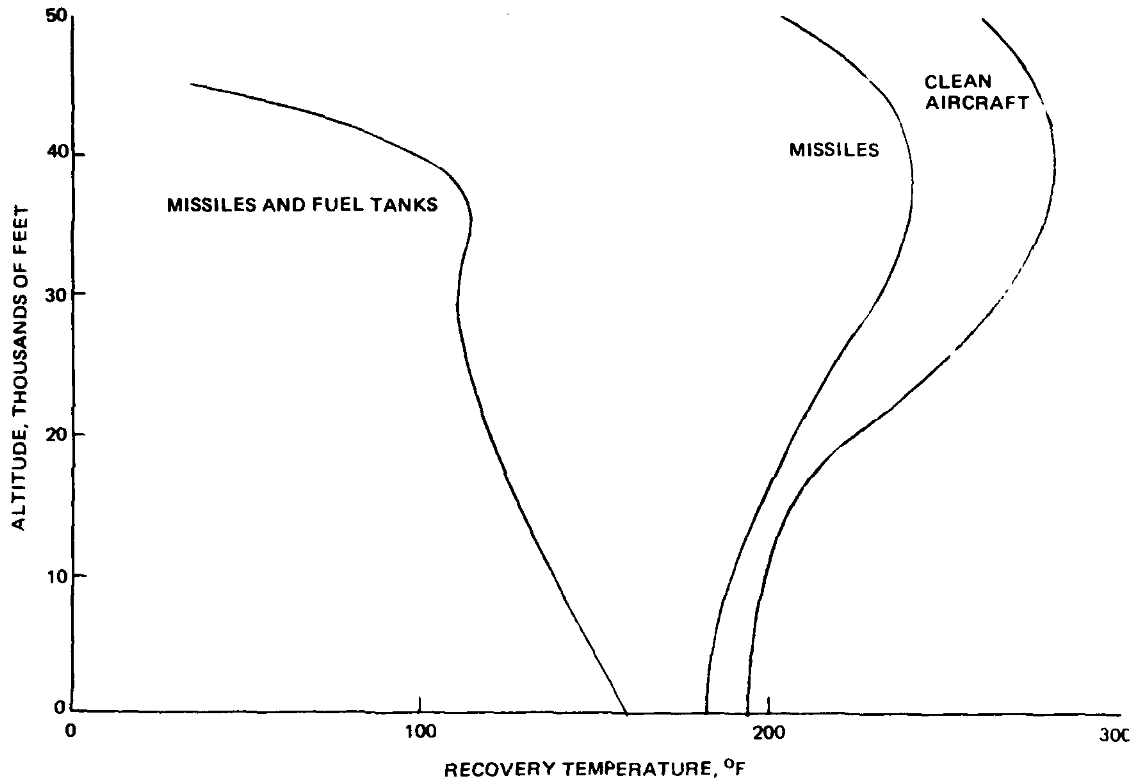

FIGURE 14. Maximum Speed Recovery Temperatures for Typical Fighter Aircraft. Standard Atmosphere.

about 230°F. Adding fuel tanks perhaps necessary for the fighter to reach its target reduces the recovery temperature still further.

A typical effect of atmospheric temperatures on aircraft maximum performance capabilities and resultant recovery temperatures is shown in Figure 15. The maximum Mach number is shown in the figure on the left-hand side with the solid line for a standard day, as is usually presented in the airplane flight manual. A hot day can reduce this maximum Mach number as shown by the dashed line. Similarly, a cold day can increase the maximum Mach number as shown. The corresponding recovery temperatures are shown on the right-hand side of the figure. At altitude the hot day recovery temperatures are significantly lower than the cold day recovery temperatures.

Minimum captive carry temperatures would be obtained under high altitude cruise conditions where Mach numbers are moderate but the altitudes are high enough that extreme cold atmospheric conditions are encountered. Maximum endurance flights usually take place at more moderate altitudes but are flown at very low Mach numbers. On the high end of the temperature scale, maximum Mach number flights are usually of short duration and can be moderated by hot atmospheric temperature conditions. The type of mission determines the flight conditions to a large extent. But these conditions are not only influenced by the stores carried and atmospheric temperature as described above but also by pilot technique. A pilot might not tend to fly at some of the very low Mach numbers that could result in maximum endurance because it is not comfortable to fly an airplane at low speeds which may be near the stalled condition. Also, maximum Mach number flights at low altitude in turbulent conditions can be a punishing experience when extended for any length of time. Fuel usage at high Mach number flight is a definite limiting factor on the length of such high speed conditions. Even when high speed flight is extended by in-flight refueling, it is necessary to slow down during the refueling process.

An example of the discussion given above can be seen in Figure 16. The normal combat operating range of a typical attack aircraft, as described by a pilot thoroughly experienced in the aircraft, is shown on a Mach number-altitude plot. The cruise and even combat conditions are well within the maximum and minimum speeds as described by the pilot (and confirmed in the aircraft operating manual). In addition, the pilot has indicated a buffet speed above the minimum level flight speed and a reduced elevator effectiveness below the maximum speed.

Figure 17 shows the performance of a modern fighter aircraft in terms of altitude and recovery temperature. The performance as given is not adjusted for temperature, but the recovery temperature (based on standard day performance) is calculated for a standard day, a 10% cold day, and a 10% hot day. One must first remember that a performance envelope calculated in this manner is actually an envelope of envelopes, since it is incorrect to assume the 10% hot or cold atmosphere for a single flight of varying altitudes. The circles on the right in the figure are calculated for maximum sustained 1-*g* flight for a light-to-medium aircraft loading. It is theoretically possible to show these conditions for an altitude that actually exceeds the service ceiling of the aircraft for the difficult to achieve clean, no fuel condition! The light, medium, and heavy loading service ceilings are still lower. An important factor not

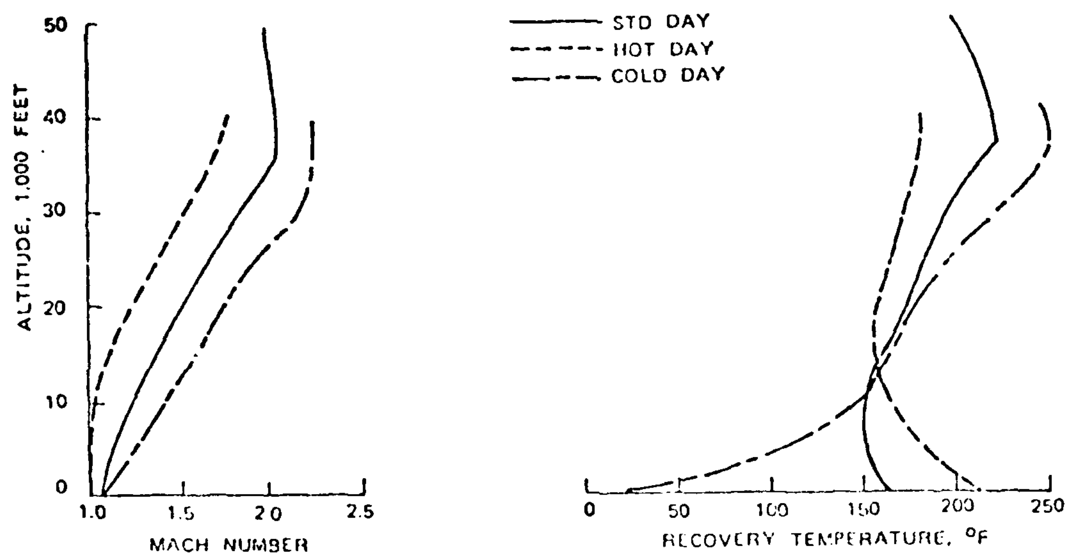

FIGURE 15. Effect of Atmospheric Conditions on Aircraft Maximum Performance and Recovery Temperature.

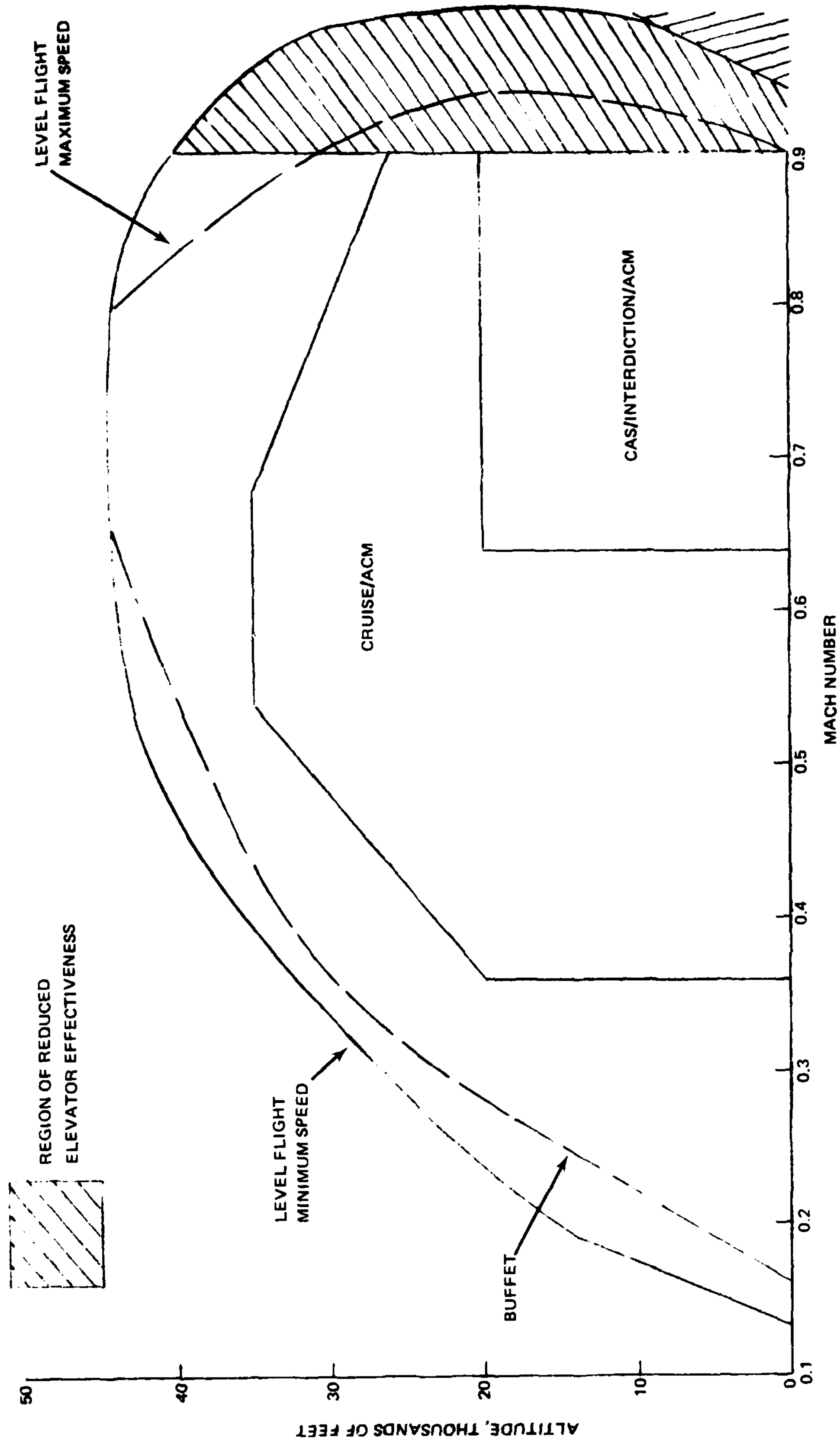

FIGURE 16. Typical Attack Aircraft Operating Range.

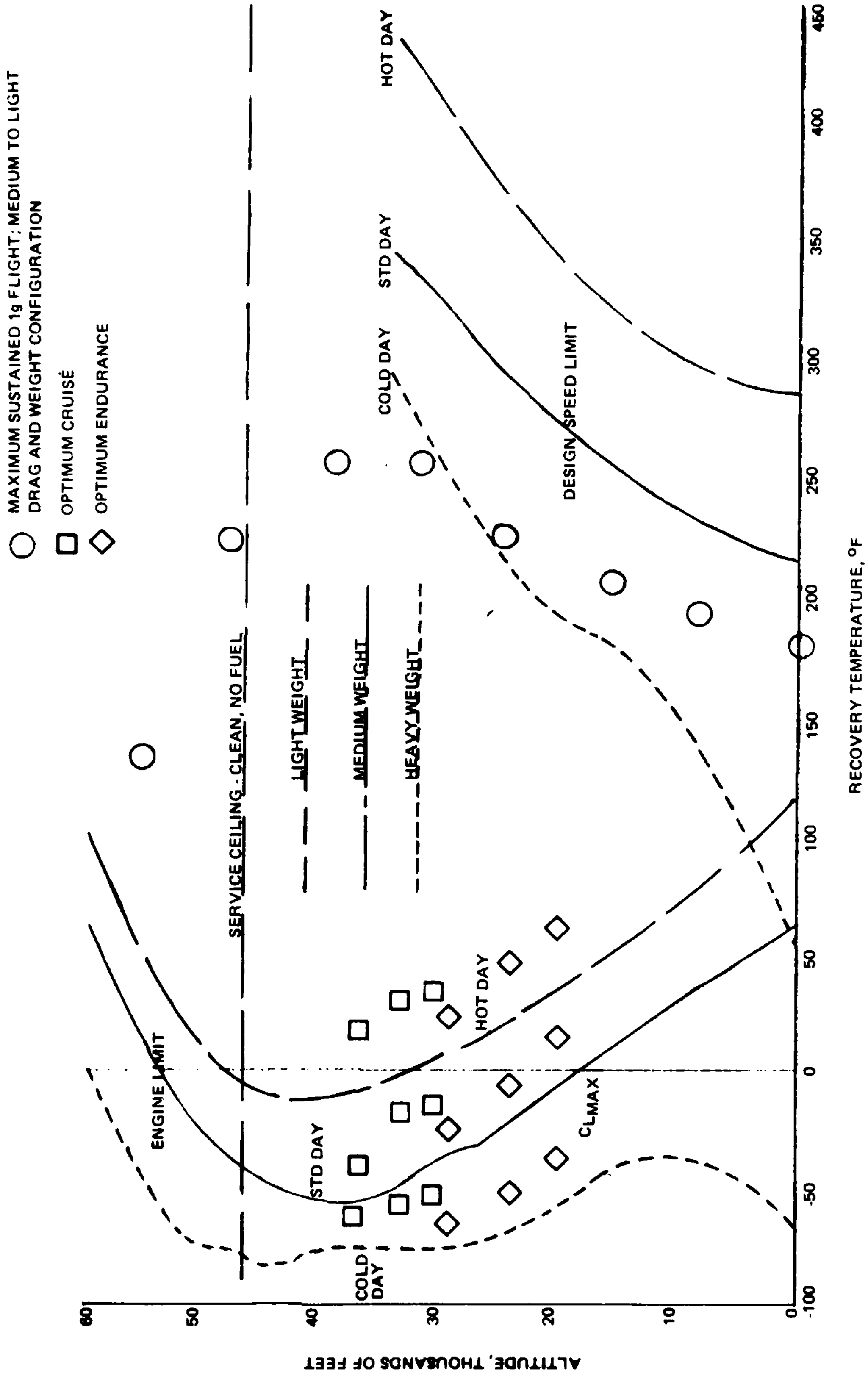

FIGURE 17. Recovery Temperature Envelope of Modern Fighter.

shown on this figure is the time at maximum Mach numbers. The recovery temperatures shown are high, but the flight times are so short due to fuel limitations that even the store skins would be unlikely to achieve these high temperatures.

The optimum cruise and endurance conditions are shown on the left side of the figure for the same three atmospheres and the three weight and store loading conditions. These theoretical temperatures are very low, but temperatures below -50°F have been measured in flight. These flight times are long enough that low soak temperatures could be achieved in the airframe and electronics components but not the warheads and rocket motors of larger missiles. It is necessary, however, to examine the probabilities concerned with extreme atmospheres, mission profiles, and modern tactics. The heavy condition at the beginning of a flight requires a lower altitude and a higher Mach number than later in the flight. The light condition would be minimum fuel (so short duration) and would probably occur near the end of a flight when (under wartime conditions) most stores would probably have been launched.

As has been stated, most flying time in a modern military aircraft is spent away from the extremes of the operational envelope, particularly the high altitude, high Mach number side of the envelope. A statistical tally of flight hours at various values of altitude and Mach number is shown in Figure 18 for a typical fighter aircraft. Most of the flight hours are flown at subsonic speeds. Minimum temperatures will occur during subsonic flight at high altitude. Because of fuel limitations, supersonic captive flight times are relatively short, as shown by the frequency diagram, and significant internal heating of most missile components does not occur. A worst case from an internal heating standpoint can be high subsonic flight at low altitude where high aerodynamic heat transfer coefficients and long flight times combine with relatively high recovery temperatures to produce a severe thermal environment.

As implied above, the mission profile and the tactics employed have a strong influence on the store temperatures achieved in captive carry. Modern tactics are in a changing state and are highly classified, but it is generally known that the trend is toward low altitude, high Mach number flight. An example of a high altitude ingress and egress deep air support mission for a currently operational attack aircraft is shown in Figure 19 in terms of recovery temperature for the three atmospheres. Once again it must be kept in mind that the use of the extreme atmospheres at varying altitudes makes this mission profile plot an envelope of extremes for this mission. The cruise out condition is at a higher Mach number and lower altitude than the lighter cruise back condition, with resulting lower temperatures for the cruise back condition. Also the high speed, low altitude portion of the flight is for a very abbreviated time period. Under wartime conditions, stores would probably be launched during this portion of the flight. But for peace time conditions and even some wartime conditions, the return flight should be considered. Figure 20 shows a recovery temperature history for a typical fighter aircraft. The decreasing flight times as recovery temperatures increase are due to increased fuel consumptions at the flight conditions that generate high recovery temperatures.

Another very specialized captive carry condition that needs to be considered is one in which stores are carried on multi-engine V/STOL aircraft. Such an aircraft creates, in the

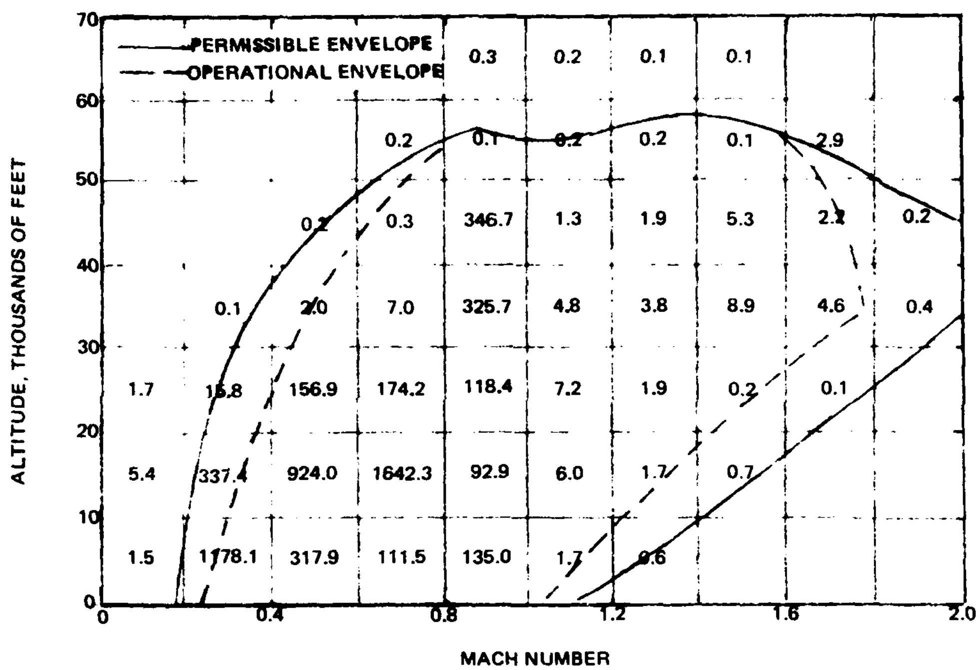

FIGURE 18. Frequency in Flight Hours.

FIGURE 19. Recovery Temperature Profile - Deep Air Support Mission.

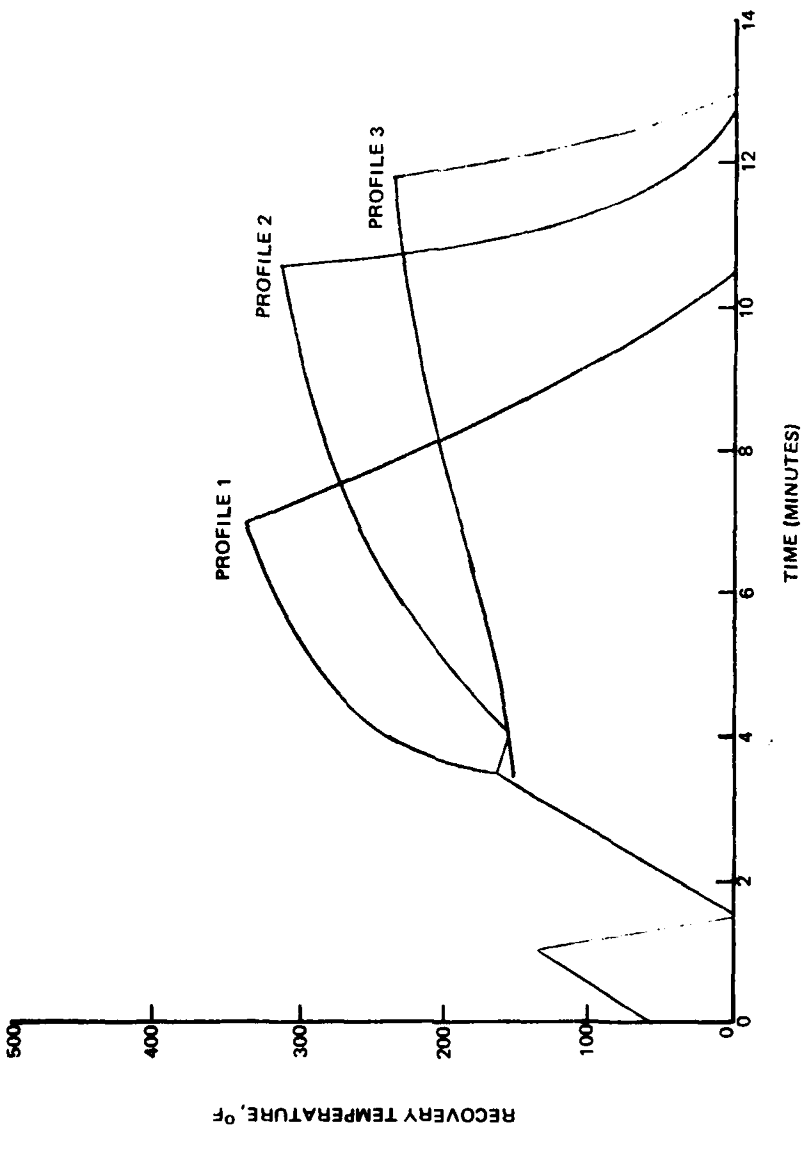

FIGURE 20. Recovery Temperature History - Typical Fighter Flight Profile.

lift-off process, a series of free jets which impinge the ground where they form wall jets. Under certain geometric and altitude conditions, these wall jets can meet in a central location to form a fountain flow which returns to the aircraft. Depending on the times involved, as well as the engine exit nozzle temperatures, these hot gases in the fountain could significantly elevate the store temperature. A sketch of this complex flow field is shown in Figure 21.

Other aerodynamic conditions that should be considered in captive flight (and free flight also) are the interference effects, one of the most serious of which can be shock impingment. The shock from the launcher or adjoining stores, for example, can impinge upon the missile and cause surprisingly large local increases in heating, even by orders of magnitude. Much work, both analytical and experimental, has been performed on interference heating, but accurate, reliable engineering prediction techniques are not yet available. An example of some experimental work taken from published work[22] is shown in Figure 22. Tests on this instrumented store in captive flight have shown pressure increases in the vicinity of the launcher which correspond to increases in heat transfer coefficient of over twice the undisturbed value. Other interference effects include corner flow (in the vicinity of fins, fuselages, etc.), protuberance flow, and cavity flow.

The task of predicting the thermal environment a store will see in captive flight is complex and dependent upon forecasting mission profiles and predicting probabilities of many intertwining factors. Calculating the thermal response of a store during a known flight is an easier but still difficult and complex task in interfering flow fields or at angle of attack. Nevertheless, moderate success has been achieved in this regard as evidenced by correlation between prediction and measurements.[23,24]

FREE-FLIGHT ENVIRONMENT

Discussions to this point have addressed the problem of determining the thermal state of the store at launch. The captive carry portion of the flight determines the temperature distribution of the missile at launch; however, free flight creates the most severe aerodynamic heating and thus is usually of primary concern to the thermal analyst. It is in free flight that the store must function properly. Excessive temperatures for a long enough period of time can cause failure or degradation in the guidance system, propellant or warhead and result in failure of the mission. At the other extreme, overdesign due to excessively severe assumed or calculated environments can result in cost overruns or even inability to meet performance requirements necessary to successfully accomplish the design mission.

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[22] C. E. Markarian. "External Store Pressure Distributions During Captive Flight Aboard an F-4B Aircraft." Presented at AIAA Sixth Aerodynamic Testing Conference, March 1971. (Paper No. 71-295, publication UNCLASSIFIED.)

[23] Naval Weapons Center. *Comparison of HARM FDTV Flight Test and Analytical Results*, by B. M. Ryan. China Lake, CA, NWC, 31 July 1978. (NWC Memo Reg 3161-46-78, publication UNCLASSIFIED.)

[24] ------. *Assessment of the Comparison Between HARM FDTV Flight Data and Predictions*, by B. M. Ryan. China Lake, CA, NWC, 21 September 1978. (NWC Memo Reg 3242-14-78, publication UNCLASSIFIED.)

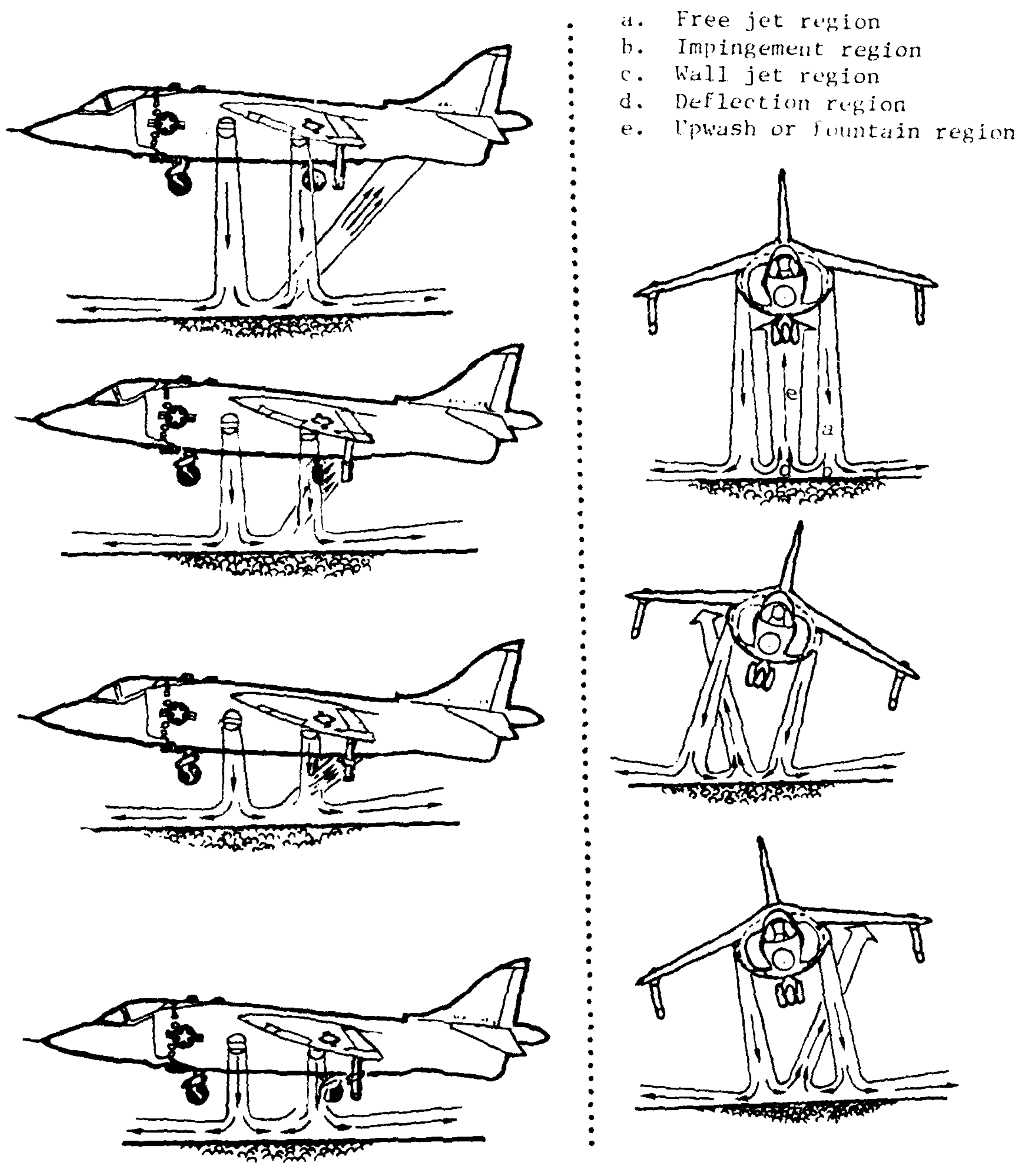

FIGURE 21. V/STOL Flow Field.

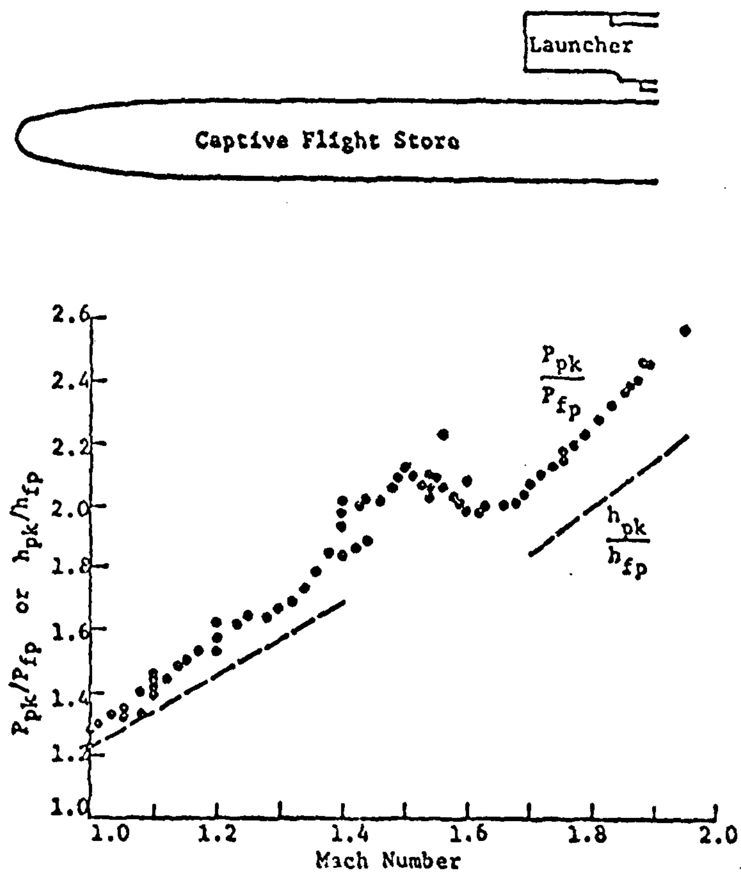

FIGURE 22. Peak Pressures and Heat Transfer Coefficients in Shock Impingement Regions.

Free-flight aeroheating analysis is complicated by the fact that many possible trajectories must be analyzed to identify specific problem areas for various components. Trajectories are screened for those producing maximum airframe temperatures, worst-case combinations of temperatures and loads, maximum thermal stresses, and maximum internal temperatures. The latter was not an important factor in early air-launched missiles because flight times were not long enough to cause significant internal thermal response. Current and future planned longer range, higher speed systems, such as those utilizing ramjet propulsion, can create major internal heating problems. At the present time there is no systematic way of selecting worst-case trajectories (in combination with appropriate atmospheres). "Brute force" methods are often utilized by examining individual trajectories or by the slightly more sophisticated technique of comparing a large number of trajectories by computer. This is still a brute force technique made easier and more accurate by ever-increasing computer capabilities. Perhaps a better method would be to apply optimization or variational techniques. More effort is needed in this regard.

As in captive flight, interference effects must be considered in free flight. In this regime the interference can come from other parts of the store. Some specific interference problems include shock impingement; control surface interactions, including the effect of geometry change; corner flow (intersection parallel to the fluid flow); impinging vortex due to both shed vortices and the vortex formed by shock wave intersections; and rotational flow due either to the vortices present in a flow caused by blunt leading edges or to the vortical layer formed behind a curved shock. A description of these problems and a survey of some of the solutions from the literature have been published.[25] Additional interference problems include cavity flow, general separation, flow around protuberances, base flow, flow around spikes, wake flow, and flows containing suction and/or injection. None of these problems has been solved, and extensive further effort is needed.

Transition is another complex and unsolved problem that must be considered in any thermal analysis. The change from laminar heating rates to the higher turbulent heating rates creates lateral gradients in the transition region, but more important are the higher gradients through the wall. Transition is particularly important as it affects missile seeker domes. The high thermal stresses induced by transition can increase the probability of thermostructural failure of ceramic IR/EO domes and radomes. Resulting thermal gradients can have detrimental effects on the optical and electromagnetic performances of seeker domes. A calculation for the IR/EO smooth dome case is shown in Figure 23. The plot on the left shows the inner wall temperature around the dome from the stagnation point aft. One calculation is for all laminar flow and the other is for transition about 30 degrees back. Corresponding values for stress around the dome are shown in the plot on the right-hand side of the figure. This stress at transition would be enough to break the dome.

In order to determine if a problem existed for this particular dome, a flight test was conducted in which the inner wall temperature distribution of the dome was measured in

[25] Naval Weapons Center. *Summary of the Aerothermodynamic Interference Literature*, by B. M. Ryan. China Lake, CA, NWC, April 1969. (NWC TN 4061-160, publication UNCLASSIFIED.)

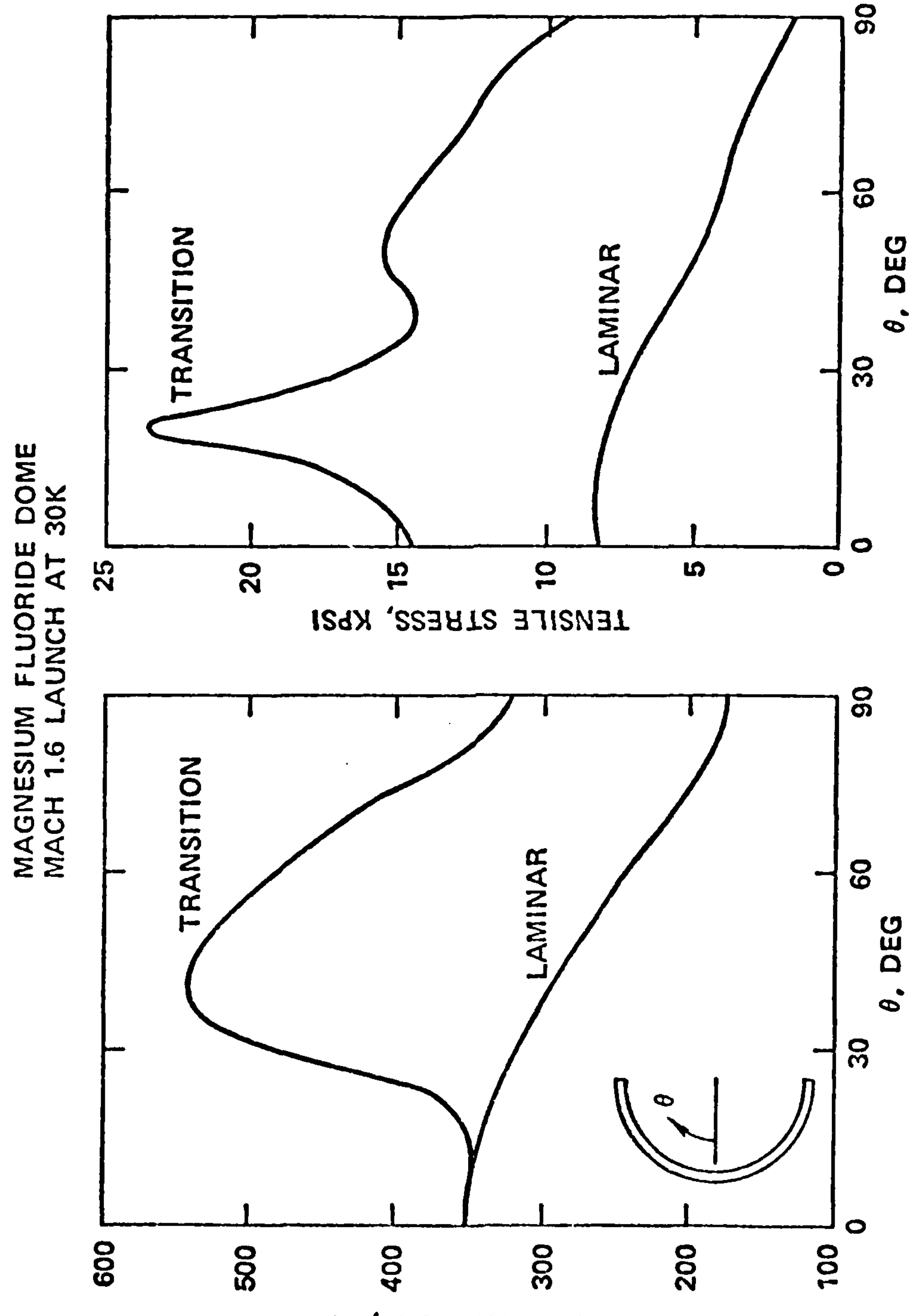

FIGURE 23. Effect of Boundary Layer Transition on Inner Wall Temperature and Stress.

free flight. The flight conditions were used to calculate the temperature, assuming both an all-laminar boundary layer and a transitional boundary layer. The results are shown in Figure 24. The test data correlated with the all-laminar calculation and indicated, at least for this case, that transition did not occur on the dome.

Because of these questions and because the flight test applied to only one restricted case, a rather extensive investigation was initiated to develop engineering techniques to predict the location and extent of transition on IR/EO hemispherical domes.[26] Literature covering in-depth investigation of this long-standing problem was studied, but no existing solution was found. However, some relevant conclusions were reached. It is now generally recognized that transition in ground test facilities is dominated by noise, and such data cannot presently be used to predict transition in flight. Enough flight information exists, however, that when it is combined with intuition, one may conclude that transition probably does not occur on smooth, hemispherical domes of moderate diameter (say, less than 5 inches) in the Mach number range to about mid-supersonic. It is believed that transition on a smooth dome would take place at the shoulder where the boundary layer would be tripped by the changing geometry. On a radome which does not have the highly polished surface of an IR dome, the entire surface would probably have turbulent flow, especially on configurations which have a rain erosion tip on the nose. Thus, it is currently believed that the high thermal gradients associated with transition are not a problem for current or near-future missiles.

The conclusion of this investigation (not to use transition results from general facilities to predict transition in flight) was recently reinforced by two papers reporting on many years of effort in transition studies. Both these efforts are concerned with sharp cones, but the conclusions may apply at least in a general sense to other configurations.

Pate[27] reported on a long-term study relating wind tunnel disturbances to boundary layer transition. His major conclusion is:

> "Experimental studies have shown that free stream disturbance intensities present in subsonic-transonic-supersonic-hypersonic wind tunnels have a dominating effect on boundary-layer transition on simple geometries."

Dougherty and Fisher[28] took a 10-degree sharp cone that had been tested in 23 wind tunnels and made careful flight measurements on it to define transition location. Comparisons were made with the wind tunnel results, and marked differences were found.

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[26] Naval Weapons Center. *Boundary Layer Transition Data With Emphasis on Application to Missile Seeker Domes*, by B. M. Ryan. China Lake, CA, NWC, December 1975. (NWC TN 4061-178, publication UNCLASSIFIED.)

[27] S. R. Pate. "Effects of Wind Tunnel Disturbances on Boundary-Layer Transition with Emphasis on Radiated Noise: A Review." Presented at AIAA Eleventh Aerodynamic Testing Conference, Colorado Springs, CO, 18-20 March 1980. (AIAA Paper 80-0431, publication UNCLASSIFIED.)

[28] N. S. Dougherty, Jr., and D. F. Fisher. "Boundary Layer Transition on a 10-Degree Cone: Wind Tunnel/Flight Data Correlation." Presented at AIAA Eighteenth Aerospace Sciences Meeting, Pasadena, CA, 14-16 January 1980. (AIAA Paper 80-0154, publication UNCLASSIFIED.)

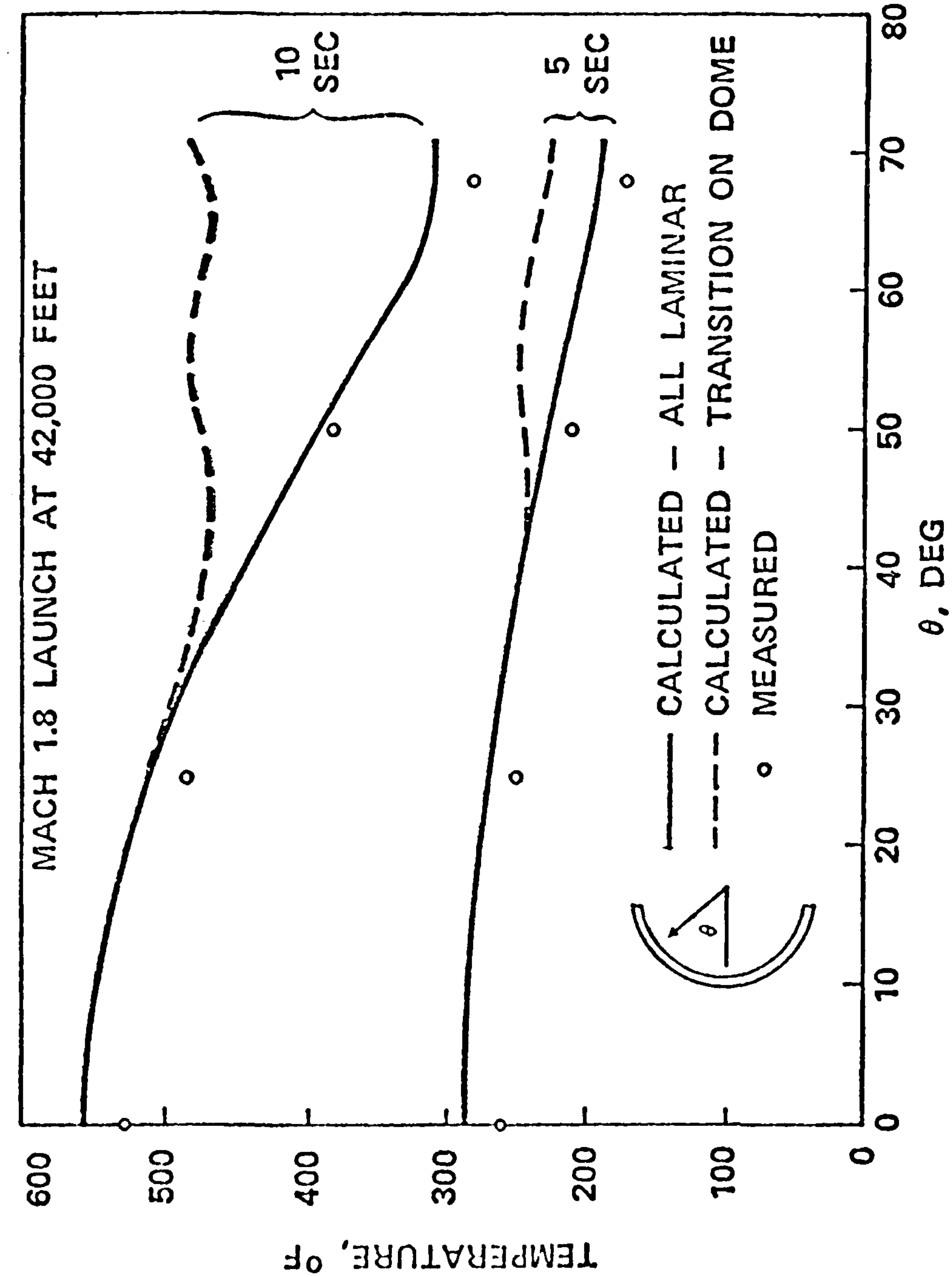

FIGURE 24. IR Dome Inner Wall Temperature Distribution.

The most significant difference in environment was the free stream disturbance level in flight as compared with even the most quiet wind tunnels. Their main conclusion was:

> "Transition Reynolds numbers in the quietest wind tunnels were about the same as those in-flight at the low subsonic Mach numbers, began to deviate at high subsonic Mach numbers, and were 25-percent lower approaching Mach 2.0. In the noisier wind tunnels, Re_T (end of transition length Reynolds number) was as much as a factor of two lower than flight."

SUMMARY AND RECOMMENDATIONS

An overview has been presented on the general philosophy and techniques in use at NWC for determination of the thermal environment which is fundamental to the aerothermodynamic analyses of air-launched missiles. The storage environment can be predicted with confidence if the storage conditions are known. More information on individual weapons is needed with respect to their storage location and the conditions of loading onto the aircraft prior to flight. The captive flight environment as it relates to carrying aircraft performance has been well-characterized for current airplanes but needs to be published as a detailed handbook which can be updated as additional information is available. More effort is needed in determining nonstandard-day performance of these aircraft with stores. Further data on mission profiles and tactics, including hours flown, is required in order to define more realistic aerothermal environments for stores. When the environment is known, the ability to get good correlations between analysis and experiment has been demonstrated.

The most important part of the aerothermal environment discussed in this overview is the free-flight portion. The most severe heating takes place in this regime, particularly in application to advanced systems. As in the case of captive flight heating, the critical phase is in selecting the atmosphere and flight profiles. A systematic technique for selecting worst-case flight trajectories should be developed. Some of the possible thermal problems encountered in free flight have been discussed, but more effort needs to be extended in determining the seriousness of these problems and others that may be present. With this knowledge, the thermal protection/control requirements can be determined.

NOMENCLATURE

$C_{L_{max}}$	Maximum lift coefficient
g	Height dependent acceleration of gravity g_o at sea level $= 9.80665\ m/s^2$ $= 32.1741\ ft/sec^2$
H	Geopotential altitude $H = \int_0^z \frac{g}{g_o}\, dz$ Note: Geopotential altitude is used in this report (and in thermodynamic calculations). For an explanation see References 2 and 5. The difference between the two altitudes is less than 1/2% at 100,000 feet but increases with altitude.
h	Heat transfer coefficient (Btu/hr-ft^2 °F)
k	Boltzmann constant $= 1.380622 \times 10^{-23}$ N·m/K $= 1.832930 \times 10^{-23}$ ft-lb/°R
M	Constant mean molecular weight
M	Mach number
N_A	Avogadro constant $= 6.022169 \times 10^{26}$ (kg-mol)$^{-1}$ $= 2.73179 \times 10^{26}$ (lb-mol)$^{-1}$
P	Total pressure, P_o at sea level $= 1.013250 \times 10^5$ Pascal (N/m) $= 2116.217021$ lb/ft^2
P_r	Prandtl number (usually about 0.71 for air)
q_{atm}	Atmospheric radiation (Btu/hr ft^2)
q_{solar}	Solar radiation (Btu/hr ft^2)
R*	Universal gas constant $= 8.31432 \times 10^{-3}$ N·m/(k mol-°K) $= 1545.31$ ft-lb/(lb mol-°R)
r	Recovery factor $r = \begin{cases} 1, & \text{stagnation point} \\ \sqrt{Pr}, & \text{laminar flow} \\ \sqrt[3]{Pr}, & \text{turbulent flow} \end{cases}$
r_o	Effective earth radius $= 6356.766$ km $= 3949.911$ st mi
s	Sutherland constant $= 110$ K $= 198.72$ °R
T	Total temperature, T_o at sea level $= 288.15$ K $= 15$°C $= 518.67$ °R $= 59$°F

T_{amb}	Ambient air temperature (absolute units for recovery temperature calculation)
T_r	Recovery temperature = $T_{amb} (1 - \frac{\gamma - 1}{2} rM^2)$
T_{skin}	Skin temperature
Z	Geometric altitude
α_L	Long wave absorptivity (usually selected as 0.9)
α_S	Solar absorptivity (usually about 0.25 for white painted surfaces, 0.6 to 0.8 for gray painted surfaces and 1 for black surfaces)
β	Another Sutherland constant = 1.458×10^6 kg/(s·m·K$^{1/2}$)
γ	Ratio of specific heat of air at constant pressure to specific heat of air at constant volume = 1.400
ϵ	Emissivity (varies with surface but usually taken as 0.9)
ρ	Total density, ρ_0 at sea level = 1.2250 kg/m^3 = 0.076474 lb/ft^3
σ	Mean effective collision diameter = 3.65×10^{-10} m = 1.1975×10^{-9} ft
σ	Stefan-Boltzmann constant = 0.1714×10^{-8} Btu/hr ft^2 °R^4

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